United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Table of Contents

Chapter 1 -- Introduction
Chapter 2 -- Sediment Properties
Chapter 3 -- Erosion
Chapter 4 -- Transmission of Sediment by Water
Chapter 5 -- Deposition of Sediment
Chapter 6 -- Sediment Sources, Yields, and Delivery Ratios
Chapter 7 -- Field Investigations and Surveys
Chapter 8 -- Sediment-Storage Design Criteria
Chapter 9 -- Units and Equivalents

United States Department of Agriculture

Soil Conservation Service

P.O. Box 2890
Washington, D.C.
20013

December 12, 1983

NATIONAL ENGINEERING HANDBOOK, SECTION 3 (Second Edition)
210-VI

SUBJECT: ENG - SECTION 3, SEDIMENTATION

Purpose. To replace Section 3.

Effective Date. Effective when received.

Explanation. All the old chapters have been revised, some chapters renumbered, and some new chapters added.

Filing Instructions. Remove and discard existing Section 3 and replace with enclosed Section 3, Second Edition.

Ordering Instructions. Additional copies may be ordered from Central Supply using order number NEH-003, Second Edition.

Paul M. Howard

PAUL M. HOWARD
Deputy Chief for Technology
Development and Application

Enclosure

DIST: NEH-003

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

NO-ADS-4
9-80

DISTRIBUTION AND CHECK LIST

STATE	
AL-01	10
AK-02	5
AZ-04	10
AR-05	10
CA-06	20
CO-08	10
CN-09	5
DE-10	5
FL-12	5
GA-13	10
HA-15	5
ID-16	10
IL-17	10
IN-18	10
IA-19	10
KS-20	10
KY-21	10
LA-22	10
ME-23	5
MD-24	5
MA-25	5
MI-26	5
MN-27	10
MS-28	10
MO-29	10
MT-30	10
NE-31	10
NV-32	5
NH-33	5
NJ-34	5
NM-35	10
NY-36	10
NC-37	10
ND-38	10
OH-39	10
OK-40	15
OR-41	10
PA-42	10
PR-72	5
RI-44	5
SC-45	10
SD-46	10
TN-47	10
TX-48	15
UT-49	10
VT-50	5
VA-51	10
WA-53	10
WV-54	10
WI-55	10
WY-56	10
Total States	455

TSC'S	
MTSC-63	25
WTSC-64	25
NETSC-61	25
STSC-62	25
Total TSC Staff	100
NHQ Engineering	25
OTHER	
Central Supply - 4420	
Robert Shelton - 500	
Grand Total SCS	5500

REMARKS

United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Chapter 1

Introduction

Contents

	Page
Purpose and scope	1-1
Responsibilities of SCS geologists	1-2

Chapter 1
Introduction

Purpose and Scope

This section of the National Engineering Handbook presents in brief and usable form applications of the principles of geology and hydraulic engineering to the solution of sedimentation problems encountered in programs of the Soil Conservation Service (SCS). These programs and the sedimentation investigations that serve them require a versatile approach.

Section 3 is necessarily limited to aspects of sedimentation that pertain directly to SCS programs. Emphasis is, therefore, given to problems affecting the evaluation of erosion and sediment-storage damages, formulation of programs for reducing these damages, and sediment-storage design criteria for structural works of improvement for the beneficial use, control, and conservation of soil and water resources. References at the end of each chapter list some of the more important literature related to the topic of that chapter.

To help geologists acquire a complete understanding of a problem and make the investigations and computations necessary for a technically sound solution, this section describes typical problems arising in sedimentation investigations and outlines basic considerations and step-by-step procedures for solving them. These examples will help in training SCS geologists and in maintaining uniform procedures and standards for SCS work.

Knowledge of sedimentation and its application to the planning and operation of SCS programs is relatively new. Insufficient research contributes to uncertainty about approaches to some problems. Although specific examples are not included, possible approaches to these problems are outlined to assist geologists in reaching reasonable solutions. Procedures found to be adequate for use nationally are outlined in detail and can be considered standard for SCS work.

Responsibilities of SCS Geologists

The primary responsibilities of geologists in SCS programs are sedimentation investigations, damsite explorations, and ground-water investigations. General information, methods, and procedures to be used by geologists are presented in three sections of the *National Engineering Handbook*: Section 3, Sedimentation; Section 8, Engineering Geology; and Section 18, Ground Water.

Section 3 is designed to help geologists select and follow procedures for making sedimentation investigations. Geologists are responsible for making the required investigations in enough detail to provide sound and factual information that supports their recommendations. Depending on the seriousness of the problem, the degree of investigation can range from a brief reconnaissance of the area to detailed measurements of erosion and the effects of sediment.

The objective of this section is to provide general guidance for making sedimentation investigations. Geologists must assemble information through observation, experience, and comparison with similar areas in the vicinity. No fixed method of investigation should be substituted for thinking. When there is doubt about the proper methods of solving sedimentation problems, the advice of the national technical center (NTC) sedimentation geologist should be sought.

United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Chapter 2

Sediment Properties

Contents

	Page
General	2-1
Derivation of sediments	2-2
Disintegration	2-2
Decomposition	2-2
Carbonation	2-3
Hydration	2-3
Oxidation	2-3
Solution	2-3
Soil formation	2-3
Particle characteristics	2-5
Size	2-5
Shape	2-5
Specific gravity	2-5
Size distribution of sediments	2-8
Fine-grain separation	2-8
Sieve separation	2-8
Fall velocity	2-8
Bulk properties	2-11
Sorting	2-11
Glacial and other ice-action deposits	2-11
Alluvial fans	2-11
Alluvial deposits	2-11
Beach deposits	2-11
Colluvial deposits	2-11
Marine sediments	2-11
Eolian deposits	2-12
Lacustrine deposits	2-12
Chemical deposits and evaporites	2-12
Texture	2-12
Volume-weight	2-13
Stability of sediment deposits	2-13
Porosity	2-13
Permeability	2-14
References	2-17

Figures

Page

2–1. Dimensions required for sphericity and roundness calculations 2-7
2–2. Grain-size distribution graph 2-9
2–3. Settling rates of sediment particles 2-10

Tables

Page

2–1. Chemical weathering products of common rock-forming silicate minerals 2-4
2–2. Common minerals: their hardness, specific gravity, and frequency of occurrence in average igneous rocks and sediments 2-6
2–3. Sediment grade scales 2-7
2–4. Volume-weight of reservoir sediment 2-14
2–5. Approximate average porosity of various formations 2-14
2–6. Permeability and porosity as related to grain-size distribution 2-15

Chapter 2
Sediment Properties

General

Sediments are the products of disintegration and decomposition of rocks. Material becomes detached and is transported to a deposition site where it may be affected by solution, cementation, consolidation, or biological action.

The physical properties of sediments depend on a number of factors, including composition, texture, and structure of the original formation; topography; type of weathering; and sorting (Lobeck 1939, pp. 63-80).[1] The greatest variety of minerals and textures in sediment comes from the weathering of igneous rocks, especially from this disintegration in semiarid and arid climates. These conditions have produced great volumes of sediment containing much coarse material, including boulders, especially along mountain fronts and in intermontane valleys. These deposits commonly contain a relatively high proportion of unaltered minerals such as feldspars, amphiboles, pyroxenes, and micas. Sediments produced by erosion in more humid and deeply weathered areas generally have a finer texture and a higher proportion of minerals produced by chemical weathering.

[1]*See the list of references at the end of each chapter for more information on these sources.*

Small grains of certain minerals resistant to chemical weathering, such as zircon, quartz, rutile, tourmaline, topaz, and ilmenite, remain in sediment relatively unchanged. These detrital mineral suites may reveal the source rock type (Krumbein and Sloss 1963, p. 108). Feldspars, the most common minerals in igneous rock (Pettijohn 1957, p. 122), are much less stable and less common in sediments. In humid climates feldspars are relatively easily decomposed to form products including clay minerals, silica, and oxides of aluminum.

Weathering and deterioration of rocks are considered the primary mechanisms of sediment formation. The processes and agents causing rock deterioration are many and diverse, and only a brief summary is presented in this handbook as a guide to the proper interpretation of sediments. Participants in sedimentation surveys should understand that rock formations—igneous, sedimentary, and metamorphic, either consolidated or unconsolidated—are subject to major deterioration and alteration at or near the earth's surface.

Weathering of rocks is an adjustment to a new environment. Intrusive igneous and metamorphic rocks are exposed to weathering when erosion removes the formations covering them. The forces of weathering attack volcanic rocks and sedimentary formations exposed at the earth's surface. The rate of rock deterioration depends on many factors, including composition and structure of the formation, climate, topography (especially slope), nature of vegetal cover, and elevation. The processes of weathering have been studied by many investigators, and much information is available.[2]

Disintegration

Disintegration (physical disruption) includes all processes by which rocks are broken into smaller pieces without much chemical change. Rocks are broken either into pieces containing all their original minerals in a relatively unaltered state or into grains, each consisting of an original mineral. The result may be splitting of blocks from a formation or disintegration to sand or gravel.

Large and rapid temperature changes can disrupt rock masses. For example, forest fires can heat exposed rock rapidly, thus fracturing and fragmenting it.

Frost is a major agent in the disintegration of rocks. Water collects in voids and openings in rocks and, on freezing, increases about 9 percent in volume. This transformation of water from a liquid to a solid state can dislodge fragments of rock as large as 10 feet in maximum dimension, as found along cliffs bordering Devil's Lake, Wis. (Leet and Judson 1958, p. 81). Angular fragments a few inches across are a common result of frost action on rocks.

Relief of pressure is a disruptive force where weathering and subsequent transportation remove a load from underlying rock formations, especially on steep slopes. The same effect can be produced by landslides that remove an overlying load.

Diastrophism of any type disrupts rocks. It can cause new joint systems, widen preexisting joints, or produce movement along a fracture during an earthquake. Folding of rock formations over long periods of time can also be a disruptive force.

Products of mechanical disintegration range from large boulders to sand. Basic igneous rocks commonly yield sand and gravel composed of calcic feldspars and relatively unaltered ferromagnesian minerals.

Moving water and ice are powerful disruptive forces on rock formations in several environments. These forces include wave action along shores of seas and lakes, abrasion of the banks and beds of streams, and scouring and plucking by glacial ice. The atmosphere is also a disruptive force, especially in arid regions where rocks in exposed positions are subject to attack by winds carrying abrasive mineral particles.

Biological agents have some disruptive effects on rocks, including widening of crevices by root growth, pitting of rock surfaces by lichens, and burrowing by some animals.

Decomposition

All rocks located at or near the surface of the earth are subject to decomposition as well as disintegration. Decomposition is the breaking down of mineral components of rocks by chemical reaction. Most decomposition occurs above the groundwater table, but the processes of weathering extend down hundreds of feet in desert regions and in some regions of high rainfall.

Igneous rocks are generally susceptible to chemical attack, since they are definitely out of equilibrium with the environment near the earth's surface. Twenhofel has found that, on the average, 100g of igneous rock acquires through decomposition 5.3g of carbon dioxide, 2g of water, 0.7g of carbon, and about 1g of oxygen (Mason 1956, p. 130). The resultant rocks have lower specific gravity and higher porosity than the unweathered igneous rocks. Averages of many analyses by Clarke (1924)

[2]*Authorities on weathering processes and products include Lobeck (1939), Reiche (1950), Pettijohn (1957), and Leopold, Wolman, and Miller (1964).*

and others indicate that the weathering of igneous rocks has produced sedimentary rocks in about the following proportions: shale, 82 percent; sandstone, 12 percent; and limestone, 6 percent.

Carbonation

Carbon dioxide (CO_2) is one of the most important and most common weathering agents. It comes from the atmosphere and from organic sources. It readily unites with water to form the weak acid H_2CO_3 (carbonic acid). Carbonic acid reacts with feldspars to produce clay minerals, silica, calcite, and other relatively soluble carbonates containing potassium, sodium, iron, and magnesium. The common carbonate rocks are limestone, dolomite, and marls.

Hydration

The addition of water to many of the minerals of igneous rocks results in the formation of clay minerals, which are hydrous aluminum silicates. Many minerals formed by hydration become dull earthy masses that contrast with their former hard, crystalline nature. Hydration also nearly doubles the volume of material (Lobeck 1939, p. 76). The transformation of feldspar to kaolinite is an example.

Oxidation

Through oxidation, many secondary minerals are formed from igneous rocks. The oxides of aluminum and iron are among the most stable. The oxidation of rocks in air is accelerated in the presence of moisture. Ferrous silicates in pyroxenes, amphiboles, and olivine are oxidized by air and water to hematite (ferric oxide, Fe_2O_3). The oxidation of iron is marked by color changes from green or black to red, yellow, or brown. Oxygen combines with other elements to form sulfates, carbonates, and nitrates, most of which are relatively soluble.

Solution

Solution is important in the alteration of igneous rock. Some minerals, such as quartz and the accessory minerals, are relatively insoluble. An accumulation of quartz grains thus becomes sand or sandstone. Clays and shales contain decomposition products of the feldspars and other less common primary silicates. Some of the silica from any of the silicates may be removed in solution (see table 2–1). The ground water and streams contain more silica in solution in areas of igneous rock than in sedimentary terranes. This is so partly because quartz, which is more common in sediments, is less soluble than the other common silicates and partly because less stable silicates are somewhat desilicated in the earlier cycle of sedimentation. The basic igneous rocks, such as basalt and gabbro, contain much silica even if they lack free quartz. The silica in solution and the colloidal-size silica are carried away and may be redeposited in crevices as veins of quartz or may become a cementing material filling interstices or even a replacement mineral as in silicified wood. It has been estimated that the weight of dissolved solids carried by streams in the conterminous United States is more than 50 percent of the weight of the suspended sediment carried (Leifeste 1974).

The carbonates are important solution products. Some carbonates reach the ocean and become important constituents of marine deposits as a result of the chemical or biochemical action that produces limestones and marls.

Soil Formation

Most sediment with which SCS is concerned results from erosion of soil that has taken many centuries to form. Weathered rock and soil differ in that soil contains organic as well as mineral matter and has more than one layer (horizon) roughly parallel to the land surface. Soil formation begins when material weathered from bedrock develops two or more distinguishable horizons. Most soil profiles include three principal horizons, identified by the letters A, B, and C (Simonson 1957).

Table 2–1.—Chemical weathering products of common rock-forming silicate minerals[1]

Mineral	Composition	Important decomposition products: Minerals	Important decomposition products: Others
Quartz	SiO_2	Quartz grains	Some silica in solution.
Orthoclase	$K(AlSi_3O_8)$	Clay Quartz (finely divided)	Some silica in solution. Potassium carbonate (soluble).
Albite (sodic plagioclase) Anorthite (calcic plagioclase)	$Na(AlSi_3O_8)$ $Ca(Al_2Si_2O_8)$	Clay Quartz (finely divided) Calcite (from Ca)	Some silica in solution. Sodium and calcium carbonates (soluble).
Biotite Augite Hornblende	Fe, Mg, Ca silicates of Al	Clay Calcite Limonite Hematite Quartz (finely divided)	Some silica in solution. Carbonates of calcium and magnesium (soluble).
Olivine	$(Fe, Mg)_2SiO_4$	Limonite Hematite Quartz (finely divided)	Some silica in solution. Carbonates of iron and magnesium (soluble).

[1]From Leet and Judson (1958). Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, N.J.

Various characteristics of mineral grains composing sediments have different effects on the formation and subsequent development of deposits. Size, shape, hardness, specific gravity, chemical composition, and degree of weathering of the mineral grains affect the rate and place of deposition and the nature of the deposits ultimately formed. Table 2–2 lists some of the common minerals and their hardness, specific gravity, and relative abundance.

Size

Size is an important particle characteristic that is readily measured. Bulk properties tend to vary with particle size in a roughly predictable manner. In fact, size alone has been found to describe sediment deposits adequately for many practical purposes.

Various organizations have adopted different size classifications to meet their particular needs. Four are shown in table 1–1 of Chapter 1 in Section 8, Engineering Geology, SCS National Engineering Handbook. A grade scale based on Wentworth's classification (Wentworth 1922) was recommended by the American Geophysical Union (1947) and is reproduced in table 2–3.

Five groups of sizes are presented in this table: boulders and cobbles, gravel, sand, silt, and clay. The largest size is uncommon but is easily measured. Gravel-size particles are more important than boulders and cobbles and are transported in some streams as bedload. Gravel can be measured directly by diameter or volume or by sieving. Sand-size sediment is common and is easily sized by sieving. The finest screen, No. 200, can be used for accurate size separation of sand and silt. Silt and the other fines, the clays, are best separated by measuring their rate of fall in a fluid. Silt and clay together make up most of the suspended load in streams, and they are usually distributed uniformly throughout the depth of the stream. Clay-size particles are important in their effect on density currents and on the change in volume-weight of sediment deposits during consolidation.

Shape

The various shapes of sediment particles are formed in numerous ways. Some shapes, such as the roundness of river and beach pebbles or the facets of wind-abraded particles, indicate the environment in which they formed. Other shapes express mineralogic characteristics; examples are the curving shards of volcanic glass and the unworn crystals of many resistant minerals.

Shape is defined numerically by sphericity and roundness (fig. 2–1). Sphericity is the ratio of the surface area of a sphere having the same volume as the particle to the surface area of the particle. Sphericity is also expressed as d_n/d_s, where d_n is the nominal diameter (diameter of a sphere having the same volume as the particle) and d_s is the diameter of a circumscribing sphere. A sphere has a sphericity of 1, and all other shapes have a sphericity of less than 1 (Pettijohn 1957, p. 56).

Roundness describes the sharpness of the edges and corners of a particle and is an indication of the wear the particle has received. Roundness is defined as the average radius of curvature of the edges, r_a, divided by the radius of the maximum inscribed circle, R.

Specific Gravity

The specific gravity of a mineral is the ratio of its weight to the weight of an equal volume of water. Most sediment consists of quartz or feldspar particles, which are about 2.65 times heavier than water, so a specific gravity of 2.65 is generally considered characteristic of sediment. Heavy minerals (for example, magnetite with specific gravity of 5.18), of course, are found in many sediments, but they make up such a small percentage that their importance is minor. For SCS geologists, the chief value of heavy minerals in sediment deposits is that they provide a means of identifying the sediment source.

Table 2-2.—Common minerals: their hardness, specific gravity, and frequency of occurrence in average igneous rocks and sediments.

Mineral	Mohs scale of hardness	Specific gravity	Frequency of occurrence: Average igneous rock[1]	Frequency of occurrence: Sediment[2]
			Percent	*Percent*
Feldspars	6–6	2.6–2.8	59.5	15.6
Hornblende and pyroxene	5–6	2.9–3.3	16.8	—
Quartz	7	2.65	12.0	34.8
Micas	2–4	2.7–3.1	3.8	15.1
Titanium minerals	5–6	3.4–5.5	1.5	trace
Clay minerals		2.0–3.0	—	14.5
Dolomite	3.5–4	2.8–2.9	—	9.1
Calcite	3	2.7	—	4.2
Limonite	1–5.5	3.4–4.0	—	4.0
Apatite	4.5–5	3.2	0.6	0.4
Gypsum	1.5–2	2.2–2.4	—	1.0
Other			5.8	1.3
Total			100.0	100.0

[1]Clarke (1924).

[2]Leith and Mead (1915).

Table 2-3.—Sediment grade scales[1]

Diameter			
In millimeters	In micrometers	In inches	Class
4,096–2,048		160–80	Very large boulders
2,048–1,024		80–40	Large boulders
1,024–512		40–20	Medium boulders
512–256		20–10	Small boulders
256–128		10–5	Large cobbles
128–64		5–2.5	Small cobbles
64–32		2.5–1.3	Very coarse gravel
32–16		1.3–0.6	Coarse gravel
16–8		0.6–0.3	Medium gravel
8–4		0.3–0.16	Fine gravel
4–2		0.16–0.08	Very fine gravel
2.0–1.0	2,000–1,000		Very coarse sand
1.0–0.5	1,000–500		Coarse sand
0.50–0.25	500–250		Medium sand
0.25–0.125	250–125		Fine sand
0.125–0.062	125–62		Very fine sand
0.062–0.031	62–31		Coarse silt
0.031–0.016	31–16		Medium silt
0.016–0.008	16–8		Fine silt
0.008–0.004	8–4		Very fine silt
0.004–0.0020	4–2		Coarse clay
0.0020–0.0010	2–1		Medium clay
0.0010–0.0005	1–0.5		Fine clay
0.0005–0.00024	0.5–0.24		Very fine clay

[1]From American Geophysical Union (1947).

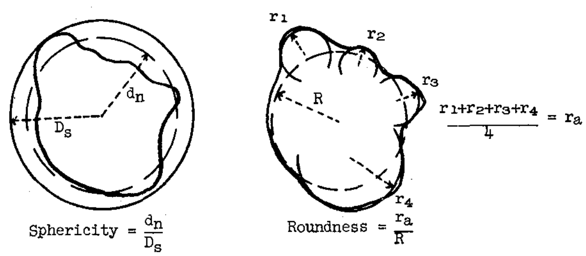


Figure 2-1.—Dimensions required for sphericity and roundness calculations.

One of the most important properties of sediment deposits is the particle-size distribution of the mineral grains. The distribution is important in predicting the behavior of sediment and estimating its specific weight. A number of precautions must be taken in studying deposits in the field and selecting samples for laboratory analysis. Laboratory studies cannot supply answers to many field problems. Problems such as selecting the beds or deposits to be sampled and determining the origin of deposits and the rate of deposition must be solved in the field. Field and laboratory data—the nature of the sediment and its texture, as well as its relationship to other formations, to soils, and to land use—must be interpreted.

The size frequency distribution of a sediment can be measured in a number of ways. The coarsest fraction is differentiated by direct measurement of gravels or larger sizes and by sieving sands. Fine-grained sediments can be separated by elutriation (the determination of settling velocity in a sediment-liquid mixture) or by microscopic examination. Detailed methods of analyzing sediments are presented by Guy (1969).

Fine-Grain Separation

One method of fine-grain separation is by timing the settling rate of sediment particles in a column of water. A suspension of the sediment sample is treated with a deflocculant such as sodium carbonate, is thoroughly mixed, and is then put into a graduated cylinder containing a column of water 800 mm high. After 10 min the upper part of the suspension is drawn off with a siphon. The coarse sediment containing grains 1/16 mm and larger remains at the bottom. This process is usually repeated about four times to achieve a clean separation. The coarse and fine separates can then be treated and studied separately.

A popular modification of the elutriation technique involves use of a bottom withdrawal tube (Howard 1948). The apparatus consists of a graduated glass cylinder with a constriction and a valve at the bottom through which the coarse particles are withdrawn. From the separation thus obtained, a cumulative curve showing size distribution can be plotted on Form SCS-ENG-353, grain-size-distribution graph (fig. 2–2). Other modifications include use of hydrometers to measure the density of the suspension at various time intervals and pipettes to withdraw fine fractions at definite time intervals.

Sieve Separation

Coarse grains (larger than 0.062 mm) are ordinarily separated by sieves having mesh openings corresponding to the grain sizes measured. The U.S. standard sieve series is based on a 200-mesh screen with a diameter of 0.074 mm. Sets of sieves with openings larger than this diameter include 0.125-mm, 0.25-mm, 0.50-mm, 2-mm, and 4-mm sizes (Twenhofel and Tyler 1941, p. 46). Grains of various sizes can be separated by this method according to the scales shown in table 2-3. The dry sample is put in the top sieve of a stack and shaken. Usually 10 min in a mechanical shaker is enough for good size separation. The material caught on each screen is weighed, and the results are expressed as a percentage of the total sample weight. For uniformity in classification of sediment texture, SCS personnel should use table 2–3 as a standard. Table 2–3 shows texture classes as standardized by the American Geophysical Union (1947).

Fall Velocity

The settling rate of particles is influenced primarily by the size, shape, and specific gravity of the particles and by the viscosity and temperature of the medium. Of these characteristics, grain size is the most important for a given fluid. The settling rates of various minerals and aggregates vary widely.

Figure 2–3 has been developed from calculations of settling velocities and laboratory measurements to illustrate the fall velocity of particles in still water at 25° C. The viscosity of water varies with temperature; settling rates decrease as temperature falls and increase as temperature rises.

Form SCS 357
9-67

LABORATORY NO. ________

MATERIALS TESTING REPORT	U. S. DEPARTMENT of AGRICULTURE SOIL CONSERVATION SERVICE	SOIL CLASSIFICATION

PROJECT and STATE	SAMPLE LOCATION
Clear Creek, Site #2, Any State	Borrow Area A

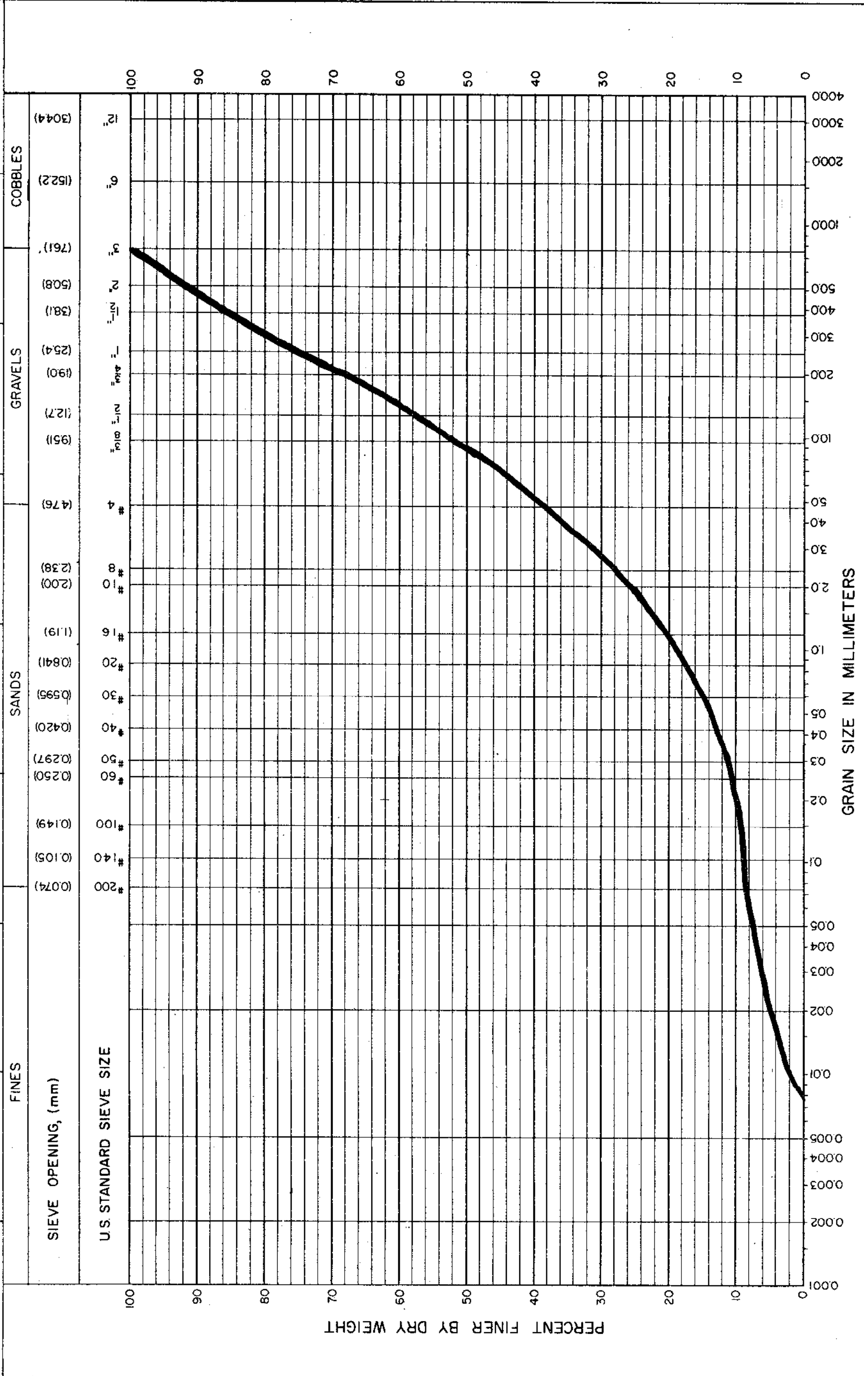
FIELD SAMPLE NO.	DEPTH	GEOLOGIC ORIGIN
151.1	3 - 5'	Alluvium (Flood Plain)

TYPE OF SAMPLE	TESTED AT	APPROVED BY	DATE
Disturbed	SML - Lincoln		1/21/78

SYMBOL	DESCRIPTION
GW-GC	Well graded clayey gravel

GRAIN SIZE DISTRIBUTION

C_c	3.0
C_u	65
D_{MAX}	3.0"
D_{85}	1 1/2"
D_{60}	13.0 mm
D_{50}	8.6 mm
D_{30}	2.8 mm
D_{15}	0.59 mm
D_{10}	0.20 mm



UNDISTURBED CONDITION		
DRY UNIT WEIGHT		g/cc pcf
MOISTURE		%

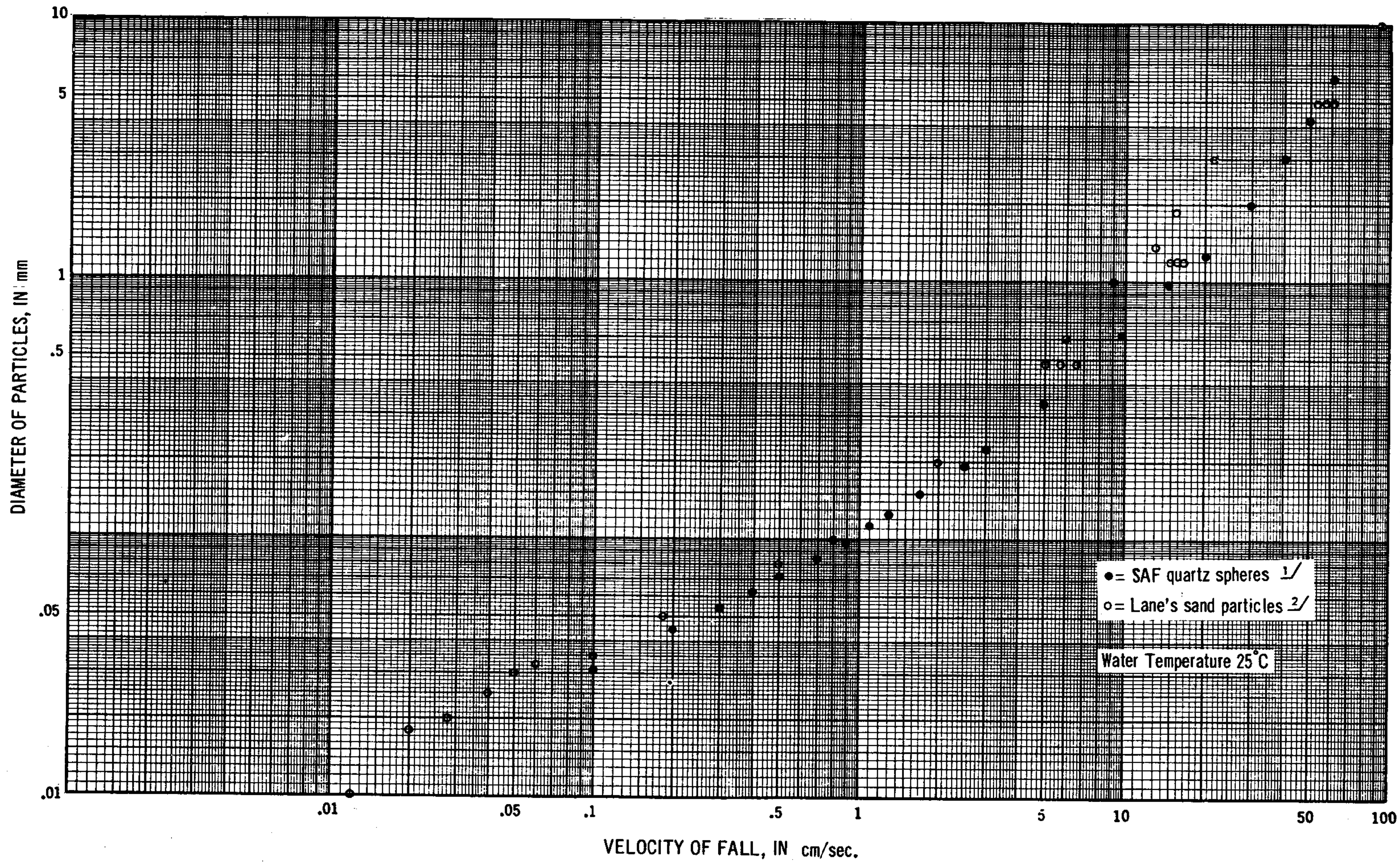
SHRINKAGE LIMIT	%
SOLUBLE SALTS	%

ATTERBERG LIMITS	LL	PI
OVEN DRY		
AIR DRY	25	10
NATURAL MOISTURE		

SPECIFIC GRAVITY (G_s)	
(+) #4	
(-) #4	

REMARKS:

Figure 2-2.—Grain-size distribution graph.



1/ INTER-AGENCY SEDIMENTATION PROJECT AT ST. ANTHONY FALLS LABORATORY (1957)

2/ LANE (1938)

Figure 2-3.—Settling rates of sediment particles.

This discussion applies primarily to unconsolidated sediments, although sedimentary deposits range from loose deposits of mineral grains to consolidated formations of similar composition that have been lithified into indurated rocks such as sandstone, limestone, and shale. Sources of sediments studied in SCS watershed investigations can be rocks, weathered zones, or soils. SCS studies of eroded and transported debris primarily involve unconsolidated, mostly uncemented sediments. The characteristics of all such formations depend on the nature and arrangement of the individual grains in the aggregate. Hence, sorting, environment of deposition, mineral species, water-holding and -transmitting capacity, and thickness of deposits affect the characteristics of the sediment deposit.

Sorting

The degree of sorting in a sediment deposit is determined by the similarity or dissimilarity of the component particles. Similarity can apply to a number of characteristics, including size, shape, specific gravity, and mineral or chemical composition. In most sediment studies the classification refers to size distribution. The engineering term "well graded" means poorly sorted and that the deposit contains a number of size grades.

The following classification includes a list of environments in which sediment deposits form, arranged approximately from the most poorly sorted to the best sorted deposits. This classification, like many others, is subject to many exceptions, some of which are indicated in the following summary descriptions. Sharp distinctions between the various groups of sediment deposits cannot be made; they all grade into the adjacent groups. Authorities on sediment sorting include Grabau (1913), Krumbein and Sloss (1963), Pettijohn (1957), and Wentworth (1922).

Glacial and Other Ice-Action Deposits

Deposits formed by glacial action are among the most poorly sorted of all sediment deposits. Glacial till, left by melting glaciers, contains fragments of all sizes, from large boulders to finely ground fragments called rock flour. Moraines and glacial outwash deposits may be more uniform, but they almost always contain much gravel, as well as sand, silt, and clay.

Alluvial Fans

A wide range of sizes is characteristic of piedmont or alluvial-fan deposits; hence, they form one of the groups of poorly sorted sediments. A lower gradient at the foot of steep slopes causes rapid deposition of most of the load of vigorous and rapid streams. Large rock blocks and boulders are commonly mixed with pebbles, sand, silt, and clay with little or no stratification.

Beach Deposits

Sorting of beach (littoral) deposits is usually poor. These deposits are primarily along shorelines and harbors along seacoasts, but they are also along the shorelines of large lakes. Locally, the sediments may be relatively well sorted and uniform in areas where conditions are stable, but in general the alternate rising and falling tides and the alternate dominance of tidal and river currents cause deposition of poorly sorted sediments. Some authorities on littoral deposits are Caldwell (1950), Grabau (1913), Mason (1950), and Trask (1950).

Alluvial Deposits

Sediments composing alluvial deposits vary greatly in size and other characteristics. Alluvial deposits can range in area from a narrow strip in a small stream valley to a great plain such as the High Plains deposit that extends east from the Rocky Mountains. In the upstream reaches of a valley where stream action is vigorous, alluvial deposits generally are coarse and poorly sorted. In the middle reaches of most streams, the coarsest and most poorly sorted parts of the alluvial deposit form in the channel. This coarse deposit is distributed to some extent over the valley bottom as the stream meanders. The deposits that occur farther downstream usually are better sorted and contain a relatively high percentage of fine sediments—fine sands, silts, and clays.

Colluvial Deposits

These products of upland erosion consist of heterogeneous materials of any particle size that accumulate on the lower part or base of slopes. Colluvium is transported there by gravity (talus), sheetwash, soil creep, and mudflows.

Marine Sediments

Marine sediments range from heterogeneous gravel and boulder deposits to vast widespread oozes in the deep sea. Deposits having the narrowest range of size distribution form where conditions of deposition remain uniform or vary only slightly for long periods. These conditions persist along slowly advancing or retreating shorelines, where great deposits of uniform sands are formed and widespread deposits of clay are laid in the deeper water. Where conditions are favorable for chemical precipitation, with or without the action of biological agents, thick and extensive deposits of carbonates accumulate. These deposits eventually become crystalline limestone or similar rock.

Eolian Deposits

Most sedimentary deposits of eolian origin are among the better sorted groups of terrestrial deposits. The following four groups of elolian deposits are recognized:

Loess.—Loess is one of the best sorted and most texturally uniform of the terrestrial deposits. Loess deposits can range from a featheredge to hundreds of feet thick and consist mainly of silt-size particles that have been transported by wind. Topographic irregularities such as a line of bluffs in a valley increase deposition. Loess deposits cover wide areas in the United States. Since they are mostly unconsolidated, they are subject to rapid erosion and gully development and they contribute to accelerated sediment deposition in reservoirs and stream channels and on flood plains.

Dunes.—Sand dunes are windblown deposits of grains moved mostly by traction or saltation, especially in semiarid and arid areas. Dunes form in areas such as lake shores, seacoasts, glacial plains, and lake beds as well as in deserts. They are generally well sorted and consist predominantly of fine- to medium-grain sands. As a result of the transporting power of the wind, the silt- and clay-size particles may be carried long distances, leaving the sand to accumulate as slow-moving dunes.

Desert pavement or wind-lag deposits.—These deposits form in many desert areas where wind removes the sand and finer textured material. The resulting surface is a thin residual concentration of wind-polished, closely packed pebbles, gravel, and other rock fragments.

Volcanic dust.—Wind caries great quantities of volcanic dust long distances after volcanic explosions. This material is well sorted; the particles that travel the farthest are all silt and clay size.

Lacustrine Deposits

Sediment deposition in lakes and reservoirs produces some of the best sorted nonmarine sedimentary deposits. The bulk of the sediment in most lakes—that found in all the larger and deeper parts of the basins, where currents are not vigorous—is almost entirely silt and clay size. These deposits are, therefore, well sorted and fine grained. The coarser and generally more poorly sorted lacustrine sediments are common along shore zones, where wave action is vigorous and coarse detritus is available, and in upstream segments, where inflowing streams deposit their coarse material.

Chemical Deposits and Evaporites

Sediment deposited from solution and evaporation is the best sorted of all sedimentary deposits. These deposits may consist of mineral crystals of almost uniform size. If organisms are incorporated in the deposit, the shells or skeletons add pieces of different sizes, reducing the degree of sorting.

Texture

The size, shape, and arrangement of the particles composing a sediment deposit determine its texture. Differences in the texture of the many types of sediment deposits cause relatively large variations in the damage that results from accelerated deposition. Coarse sediments of alluvial fans consist chiefly of gravel and boulders and cause major damage if deposited on agricultural land. Overbank flood deposits produce damage that usually increases as the texture of the deposited sediment becomes coarser. Deposits of clays and silts usually have some fertility, but they may bury crops or impede drainage if thick enough. Regardless of their texture, sediment deposits occupy valuable space in reservoirs, obstruct bridge and culvert openings, decrease stream channel and ditch capacity, and cause many other types of damage.

Differences in the texture of sediment deposits control or modify the uses for which the deposits are suited in agriculture, industry, and construction. Sand and gravel formations are the most important as aquifers and are essential materials in concrete. The uses of sand in glass manufacture, of clays in the ceramics industry, and of combinatic of sediment deposits having a variety of textures in construction are beyond the scope of this chapter, but some properties affecting earth-dam construction are described in Section 8, Engineering Geology, SCS National Engineering Handbook.

Cumulative curves (fig. 2–2) are used for presenting data on particle-size distribution. Histograms relating pyramidal curves to texture are sometimes used. Because the distribution of grain size in most samples is not symmetrical, the amount of skewness is also shown by the pyramids. This is well explained by Pettijohn (1957).

Volume-Weight

One of the most important properties of sediment deposits is weight per unit volume, or volume-weight. Volume-weight, as it applies to measurement of eroded sediment, sediment in transport, and sediment deposits in place, has primary importance in the sedimentary cycle.

Information on the unit weight of sediment deposits for construction or other purposes reflects many variations in properties. For example, a cubic foot of quartz, which has a specific gravity of 2.65, weighs about 165 lb. Similarly, a cubic foot of solid magnetite, specific gravity 5.2, weighs 324 lb. Most sediment deposits, in contrast, weigh about 25 to 125 lb/ft^3 when water free (USDA 1978). The volume-weight of sediment deposits is largely determined by the proportion of voids present. If the sediment is below the water surface, the voids are filled chiefly with water. If the sediment is exposed to the atmosphere, there are fewer voids and they are filled chiefly with air or a combination of air and water, depending on rainfall, seepage, and other factors.

Volume-weight has been measured in conjunction with many types of investigations, including construction projects, geological surveys, sedimentation surveys of reservoirs and valleys, and soil surveys.

Table 2–4 shows the average volume-weight of some typical reservoir sediment deposits (USDA 1978). This table is arranged in two parts: Part A shows the weight per cubic foot, determined by laboratory analysis, of sediment samples from reservoirs in which the water level is near the spillway crest most of the time, and Part B gives the same information for undisturbed samples from reservoirs in which sediment is exposed to the air during repeated low water levels.

Stability of Sediment Deposits

A high degree of angularity of individual sediment grains of silt size or larger promotes stability. A loose aggregation of angular grains is more stable in steeper slopes than an aggregation of more rounded grains. Similarly, angular particles in earthfills increase resistance to slumping and shear. Aggregates of mostly silt- and clay-size particles usually have predominantly angular or platy pieces, but their stability in a fill is determined more by water content and overburden pressure than by the shape of the grains. Deposits of loess, which may be tens or hundreds of feet thick and are composed of highly angular silt-size particles, tend to stand in nearly vertical faces. Deposits of more rounded grains, such as alluvial or coarse-grained eolian deposits, have lower angles of repose and are usually less stable. Deposits of platy pieces, which have an abundance of grains with two long and one short dimension, are also readily susceptible to sliding.

Porosity

Porosity has been described by Graton and Fraser (1935), Meinzer (1923), Todd (1959), and Tolman (1937) in connection with the volume and movement of ground water. According to Graton and Fraser, an arrangement of spheres providing about 49 percent pore space has the greatest porosity. This arrangement, however, is unstable. The most stable arrangement of spheres of uniform diameter provides about 25 percent pore space, but it is not found in natural sediments. Porosity exceeding 50 percent has been measured in natural sedimentary deposits.

Meinzer (1923) defines porosity in a rock or soil as the property of containing interstices or voids. The percentage of pore space is determined by the distribution of fine grains between coarser grains, the shape of the particles, and their arrangement. Grains of silt and clay size occupying spaces between sand and gravel particles can reduce porosity significantly. Both porosity and stability of sediment deposits are affected by the shape of their mineral grains. Many studies have shown that fine-grained sediments are subject to far more compaction and decrease in volume than are deposits of sand or larger grains.

Table 2–4.—Volume-weight of reservoir sediments

Name	Physiographic section	Average volume-weight (lb/ft^3)	Main stream	Nearest city
		A. Submerged sediment		
Lake Throckmorton	Redbeds Plains	31.6	Brazos River	Throckmorton, Tex.
Lake Ft. Phantom Hill	Red Hills	36.0	Clear Fork, Brazos	Abilene, Tex.
Grand Saline Reservoir	Forested Coastal Plain	38.7	Saline River	Grand Saline, Tex.
Lake Woodland	Coastal Plain	39.9	Camp Creek	DeSoto County, Miss.
Madison Lake	Central Till Plain	49.9	Ohio River	Madison, Ohio
Crab Orchard Lake	Central Till Plain	47.5	Big Muddy River	Carbondale, Ill.
White Rock	Black Prairie	49.0	Trinity River	Dallas, Tex.
Lake Williams	Appalachian Mountains	49.1	Susquehanna River	York, Pa.
Moran Reservoir	Osage Plains	49.2	Osage River	Moran, Kans.
Lake Issaqueena	Piedmont Plateau	50.9	Savannah River	Clemson, S.C.
Mountain Lake	Ozark Mountains	54.8	St. Francis River	Patterson, Mo.
Herman Lage Pond	Central Till Plain	54.8	Missouri River	Aspinwall, Iowa
Lake Harris	Piedmont Plateau	59.9	Black Warrior River	Tuscaloosa, Ala.
		B. Sediment frequently aerated		
Franklinton Reservoir	Piedmont Plateau	67.0	Sallie River	Franklinton, N.C.
White Manganese No. 6	Appalachian Mountains	87.5	Tallapoosa River	Cartersville, Ga.
Medina Lake	Edwards Plateau	75.0	San Antonio River	San Antonio, Tex.
Backbone Lake	Driftless Area	75.1	Mississippi River	Stawberrt Pt., Iowa
Lee Johnson Pond	Coastal Plain	76.1	Tallahatchie River	Holly Springs, Miss.
Castlewood Reservoir	High Plains	77.5	Arkansas River	Denver, Colo.
West Frankfort Reservoir	Central Till Plain	78.2	Big Muddy River	West Frankfort, Ill.
Gerber Lake	Sacramento Valley	78.3	Sacramento River	Corning, Calif.
Loring Lake	Coastal Plain	85.1	Mississippi River	Zwolle, La.
Cobb Creek No. 3	Osage Plains	90.0	Washita River	Colony, Okla.
Lake Medicine	Redbeds Plains	98.5	Chickaskia River	Medicine Lodge, Kans.

Table 2–5 illustrates the range in average porosity of various materials. This table does not take into account the degree of cementation or the fact that although a fine-grained deposit such as a clay may have high porosity, it permits little movement of water.

Table 2–5.—Approximate average porosity of various formations[1]

Formation	Porosity (percent)
Clay	45
Silt	40
Sand	35
Gravel	25
Shale, sandstone	18
Limestone	10
Granite, basalt	1

[1]From Leopold, Wolman, and Miller (1964).

Permeability

The permeability of sediments varies widely. Permeability is extremely low in clay materials, even though they may have high porosity and be water saturated. The interstices between the clay particles are small enough for molecular attraction to hold water tightly. Permeability is highest for coarse, clean gravel. Table 2–6 indicates the relation of permeability and porosity to grain-size distribution.

Table 2-6.—Permeability and porosity related to grain-size distribution[1]

Percent smaller than indicated grain size by weight							Porosity	Coefficient of
2.0 mm	1.0 mm	0.5 mm	0.25 mm	0.125 mm	0.062 mm	0.005 mm	(percent)	permeability (gal/day/ft^2)
—	99.4	98.4	95.4	89.7	65.0	21.0	58.2	0.0002
—	—	—	97.5	95.6	94.6	49.3	55.5	0.2
—	93.9	67.8	18.4	3.2	1.3	—	46.6	60.0
84.3	69.1	48.9	29.4	13.0	6.0	1.5	26.3	150.
77.6	59.9	34.1	10.6	0.9	[2]0.2	—	28.9	1,000.
77.7	58.1	38.4	19.3	9.6	5.3	0.9	25.0	2,095.
24.3	15.7	6.3	1.1	0.4	[2]0.2	—	23.4	4,200.
20.2	19.1	16.9	12.0	7.5	4.8	1.2	25.1	20,663.
8.4	0.5	0.4	0.3	0.2	[2]0.1	—	38.0	90,000.

[1]After Wenzel (1942).

[2]Includes clay (<0.005 mm).

References

American Geophysical Union. 1947. Report of the subcommittee on sediment terminology. Am. Geophys. Union Trans. 28:936–938.

Brown, Carl B. 1950. Sediment transportation. *In* Engineering hydraulics, p. 769–857. Hunter Rouse, ed. John Wiley & Sons, Inc., New York.

Caldwell, Joseph M. 1950. Sedimentation in harbors. *In* Applied sedimentation, p. 290–299. Parker D. Trask, ed. John Wiley & Sons, Inc., New York.

Clarke, F. W. 1924. The data of geochemistry. U.S. Geol. Surv. Bull. 770, 841 p.

Grabau, A. W. 1913. Principles of stratigraphy. A. G. Seiler & Co., New York, 1,185 p.

Graton, L. C., and H. J. Fraser. 1935. Systematic packing of spheres—with particular relation to porosity and permeability. J. Geol. 43(8):785–909.

Guy, H. P. 1969. Laboratory theory and methods for sediment analysis. *In* U.S. Geol. Survey techniques of water-resources invest., Book 5, Chap. C1, 58 p.

Happ, Stafford C., Gordon Rittenhouse, and G. C. Dobson. 1940. Some principles of accelerated stream and valley sedimentation. U.S. Dep. Agric. Tech. Bull. 695, 134 p.

Howard, C. S. 1948. Laboratory experiences with the bottom withdrawal tube method of size analysis. Fed. Inter-Agency Sediment. Conf. Proc., Denver, Colo., p. 235–243.

Kraus, E. H., W. F. Hunt, and L. S. Ramsdell. 1959. Mineralogy. McGraw-Hill Book Co., New York, 686 p.

Krumbein, W. C., and F. J. Pettijohn. 1938. Manual of sedimentary petrography. D. Appleton-Century Co., New York, 549 p.

Krumbein, W. C., and L. L. Sloss. 1963. Stratigraphy and sedimentation. 2d ed. W. H. Freeman & Co., San Francisco, Calif., 660 p.

Lane, E. W. 1938. Notes on the formation of sand. Am. Geophys. Union Trans. 19(pt. 1): 505–508.

Leet, L. D., and S. Judson. 1958. Physical geology. 2d ed. Prentice-Hall, Inc., Englewood Cliffs, N.J., 502 p.

Leifeste, D. K. 1974. Dissolved-solids discharge to the oceans from the conterminous United States. U.S. Geol. Surv. Circ. 685, 8 p.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W. H. Freeman & Co., San Francisco, Calif., 522 p.

Lobeck, A. K. 1939. Geomorphology. McGraw-Hill Book Co., New York, 731 p.

Mason, B. 1956. Principles of geochemistry. John Wiley & Sons, Inc., New York, 276 p.

Mason, Martin A. 1950. Geology in shore-control problems. *In* Applied sedimentation, p. 276–290. Parker D. Trask, ed. John Wiley & Sons, Inc., New York.

Meinzer, O. E. 1923. Outline of ground-water hydrology. U.S. Geol. Surv. Water-Supply Pap. 494, 71 p.

Pettijohn, F. J. 1957. Sedimentary rocks. 2nd ed. Harper & Bros., New York, 718 p.

Reiche, Parry. 1950. A survey of weathering processes and products. N. Mex. Univ., Publ. Geol. 3, 95 p.

Simonson, Roy W. 1957. What soils are. *In* Soil, U.S. Dep. Agric. Yearb. Agric., p. 17–31. U.S. Govt. Printing Off., Washington, D.C.

Subcommittee on Sedimentation, Interagency Committee on Water Resources. 1957. The development and calibration of the visual accumulation tube. Rep. 11, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minn., table 11, p. 99.

Todd, D. K. 1959. Ground water hydrology. John Wiley & Sons, Inc., New York, 336 p.

Tolman, C. F. 1937. Ground water. McGraw-Hill Book Co., New York, 593 p.

Trask, Parker D. 1950. Dynamics of sedimentation. *In* Applied sedimentation, p. 3–40. John Wiley & Sons, Inc., New York.

Twenhofel, W. H. 1950. Principles of sedimentation. 2d ed. McGraw-Hill Book Co., New York, 673 p.

Twenhofel, W. H., and S. A. Tyler. 1941. Methods of study of sediments. McGraw-Hill Book Co., New York, 183 p.

U.S. Department of Agriculture, Agricultural Research Service. 1978. Sediment deposition in U.S. reservoirs, summary of data reported through 1975. In cooperation with Sediment. Comm., Water Resour. Counc. Misc. Publ. 1362, 82 p.

Wentworth, C. K. 1922. A method of measuring and plotting the shapes of pebbles. U.S. Geol. Surv. Bull. 730–C, p. 91–114.

Wenzel, L. K. 1942. Methods for determining permeability of water-bearing materials. U.S. Geol. Surv. Water-Supply Pap. 887, 192 p.

United States
Department of
Agriculture

**Soil
Conservation
Service**

National Engineering Handbook

Section 3

Sedimentation

Chapter 3

Erosion

Contents

	Page
General	3-1
Sheet erosion	3-2
Factors involved	3-2
Equations	3-2
Rainfall factor (R)	3-3
Soil erodibility factor (K)	3-3
Slope length (L) and slope gradient (S)	3-3
Plant cover or cropping management factor (C)	3-3
Erosion control practice factor (P)	3-6
Water quality and sediment yield	3-6
Example of use of USLE in watershed planning	3-6
Channel erosion	3-10
Factors involved	3-10
Computation procedures	3-10
Wind erosion	3-13
Mass movement	3-14
Factors involved	3-14
Estimation procedures	3-14
Other types of erosion	3-15
Wave erosion	3-15
Erosion from strip mining and construction	3-15
Ice erosion	3-15
References	3-17

Figures

Page

3–1. Average annual values of the R factor 3-4
3–2. Slope-effect chart (topographic factor, LS) 3-5
3–3. Hypothetical 600-acre watershed used in example 3-9
3–4. Nomograph for computing average annual gully erosion, streambank erosion, channel entrenchment, and flood-plain scour in acre-feet 3-12
3–5. Projecting lines of undisturbed banks to determine probable prelake profile 3-15

Tables

Page

3–1. Values of the topographic factor, LS, for specific combinations of slope length and steepness 3-6
3–2. C factors for permanent pasture, grazed forest land, range, and idle land 3-7
3–3. C factors for undisturbed forest land 3-8
3–4. C factors for mechanically prepared woodland sites 3-8
3–5. P values for contour-farmed terraced fields 3-9

Chapter 3
Erosion

General

Erosion consists of a series of complex and interrelated natural processes that loosen or dissolve and move earth or rock material. The land surface is worn away through the detachment and transport of soil and rock materials by moving water, wind, or other geologic agents.

Erosion can be divided into two categories according to the conditions under which it occurs. The first category is normal (geologic) erosion, which has been occurring at variable rates, depending on climatic and terrestrial conditions, since the first solid materials formed on earth. Geologic erosion is extremely slow in most places. It is, in fact, an important process in soil formation. The underlying rock is attacked by air and water, and fragments are detached, decomposed, or dissolved. This process is termed weathering. Generally, a rough equilibrium is reached in natural environments between geologic erosion and soil formation. The rates of normal upland erosion and soil formation are determined mainly by climate, parent rocks, soil, precipitation, topography, and vegetal cover.

The second category is accelerated erosion caused by the activities of man. Accelerated erosion has been defined as "erosion occurring at a rate greater than normal for the site, usually through reduction of a vegetal cover" (Roehl 1965). Deforestation, cultivation, and destruction of vegetation accelerate erosion. Soil that normally would take 100 years to be eroded may vanish in 1 year or even a single day (United Nations 1953).

Both categories of erosion can be subdivided into two types: sheet and channel. This classification is helpful in (1) estimating the amount of erosion and sediment yield, (2) determining the relative importance of sediment sources, (3) formulating treatment measures to reduce erosion and sediment yield, and (4) evaluating the effectiveness of treatment measures.

In planning programs to reduce erosion and sediment yield, it is most important that the various types of erosion be thoroughly investigated as sources of sediment. Proper conservation practices and land stabilization measures can then be planned and applied.

Sheet erosion, which includes rill erosion, is the removal of soil or earth material from the land surface by the forces of raindrop impact, overland runoff, or wind. Although it occurs on all land surfaces, sheet erosion is particularly active on cultivated areas of mild slope where the runoff is not concentrated in well-defined channels but consists largely of overland flow. The numerous small but conspicuous rills caused by minor concentration of runoff are obliterated by normal field cultivation. This type of erosion occurs gradually over large areas as though the soil were removed in sheets (Bennett 1939, p. 92–115).

Materials derived from sheet erosion are fine grained because overland flow, which is usually laminar, seldom exceeds a velocity of 2 or 3 ft/s. Flow of this low velocity can transport only the fine particles detached by raindrop impact. Ellison (1945) reported a grain-size diameter of less than 0.05 mm for 95 percent of the sediment in prechannel runoff from a silt loam soil in Ohio.

Factors Involved

The basic factors in sheet erosion are rainfall, soil properties, slope length, slope gradient, and kind and condition of cover. Several equations incorporating these factors can be used to obtain a quantitative estimate of the amount of soil material moved by sheet erosion. These equations, originally developed for the humid areas east of the Rocky Mountains, are particularly well suited for determining the effects of land treatment measures on erosion.

Equations

From the late 1940's until 1972, SCS geologists, who are responsible for estimating yield, used the Musgrave Equation to compute the amount of sheet and rill erosion in a watershed. The Musgrave Equation was part of one of several procedures used to estimate sediment yield. Additional research on erosion resulted in the development of the Universal Soil Loss Equation (USLE) by the Agricultural Research Service (ARS) in cooperation with SCS and certain State experiment stations. In September 1972 the Musgrave Equation was replaced by the USLE for computing sheet erosion for project areas.

Both the Musgrave Equation and the USLE are empirical formulas in which sediment yield from subacre test plots is defined as "erosion" or "soil loss." The computed soil loss from large areas is usually greater than the sediment yield from the same area, and the larger the area, the greater the discrepancy between computed soil loss and sediment yield. Neither equation allows for deposition on upland areas. Soil loss computed by these equations represents nothing that can be located or measured in the field. It therefore is an abstract figure that must not be confused with sediment yield. Computed soil loss, however, is a valuable tool for comparing the soil loss from different areas or the effects of different land treatments on a given area.

The USLE initially was used only for cropland, hayland, and pastures in rotation, because erosion factors reflecting the effect of cover on uncultivated land areas were not available. Because the USLE had been used in much of the country as a tool in planning land treatment on individual operating units, use of this equation with its refined data was recommended for watersheds and other project areas in which SCS has responsibilities. Before this could be done, however, additional plant-cover factors (C) had to be determined for permanent pastureland, rangeland, woodland, and idle land to estimate the effect of these types of cover on soil losses.

In November 1971, SCS and ARS personnel tentatively agreed on the factors for types of cover on uncultivated lands, and subsequent analyses by ARS provided values for them. These factors are used in the USLE to estimate sheet and rill erosion for work in SCS projects such as watersheds, river basin studies, and resource conservation and development (RC&D).

The complete Universal Soil Loss Equation is

$$A = RKLSCP$$

where

A = the computed annual soil loss (sheet and rill erosion) in tons per acre. A is not the sediment yield.

R = the rainfall factor: the number of erosion index units in a normal year's rain.

K = the soil erodibility factor: the erosion rate per erosion index unit for a specific soil in cultivated continuous fallow on

9-percent slope 72.6 ft long.

L = the slope length factor: the ratio of the soil loss from the field slope length to that from a 72.6-ft length on the same soil type and gradient.

S = The slope gradient factor: the ratio of the soil loss from the field gradient to that from a 9-percent slope on the same soil type and slope length.

C = the cropping management factor: the ratio of the soil loss from a field with specified cropping and management to that from the fallow condition from which the K factor is evaluated.

P = the erosion control practice factor: the ratio of the soil loss with contouring, contour stripcropping, or contour-irrigated furrows to that with straight-row farming, upslope and downslope.

Rainfall Factor (R)

The energy of moving water detaches and transports soil materials. The energy intensity (EI) value is the product of the total raindrop energy of a storm and the maximum 30-min intensity. Soil losses are linearly proportional to the number of EI units. The EI values of the storms from a 22-year (maximum) record were summed to obtain an average annual rainfall-erosion index for a given location. This annual index serves as the R factor and can be obtained from figure 3–1, which is figure 1 in Agriculture Handbook 537 (Wischmeier and Smith 1978). This handbook also includes a procedure for determining the effect of snowmelt on the R factor.

Soil Erodibility Factor (K)

The resistance of a soil surface to erosion is a function of the soil's physical and chemical properties. The soil properties most significantly affecting soil erodibility are texture, organic-matter content, structure, and permeability. The K values assigned to named soils can be obtained from soil scientists, technical guides, or published lists.

Slope Length (L) and Slope Gradient (S)

Soil loss is affected by both length and degree of slope. For convenience in field application, these two factors are combined into a single topographic factor, LS.

The LS factor for a gradient as much as 50 percent and a slope length as much as 1,000 ft is obtained from the slope-effect chart (fig. 3–2). Similar data appear in tabular form in table 3–1. Values shown on the chart and table for slopes of less than 3 percent, greater than 20 percent, or longer than 400 feet are extrapolations of the formula to cover conditions beyond the range of research data. Computed soil loss determined from these LS values may need to be adjusted on the basis of experience and judgment.

Plant Cover or Cropping Management Factor (C)

The erosion equation, as applied to cropland and hayland, uses established factor relationships to estimate a basic soil loss that is determined by soil properties, topographic features, certain conservation practices, and expected rainfall patterns for a specific field. The basic soil loss is the rate at which the field would erode if it were continuously in tilled fallow. The C factor value indicates the percentage of this potential soil loss that would occur if the surface were partially protected by a particular combination of cover and management practices. Musgrave cover factors cannot be substituted for the C factor in the USLE because different base conditions were used to develop the cover factors (tilled continuous fallow for the USLE as opposed to uphill and downhill row crops for the Musgrave Equation).

Use of the C factor in other situations depends on three distinct but interrelated zones of influence: vegetal cover in direct contact with the soil surface, canopy cover, and the surface and beneath it.

C factor for cropland and hayland.—The C factor measures the effects of cropping sequences, cover, and management on soil losses from cropland and hayland. It is computed, on a local basis, for conventional and conservation (minimum-tillage) farming systems.

C factor for permanent pasture, grazed forest land, range, and idle land.—The effects of the three zones of influence are used in estimating the C factor for permanent pasture, grazed forest land, range, and idle land. The C factors are given in table 3–2.

C factor for forest land.—Permanent (undisturbed) forest land differs in several respects from the land for which C-factor values are given in table 3–2. A layer of compacted decaying duff or litter is extremely effective against water erosion. Research data, although limited, support a C value

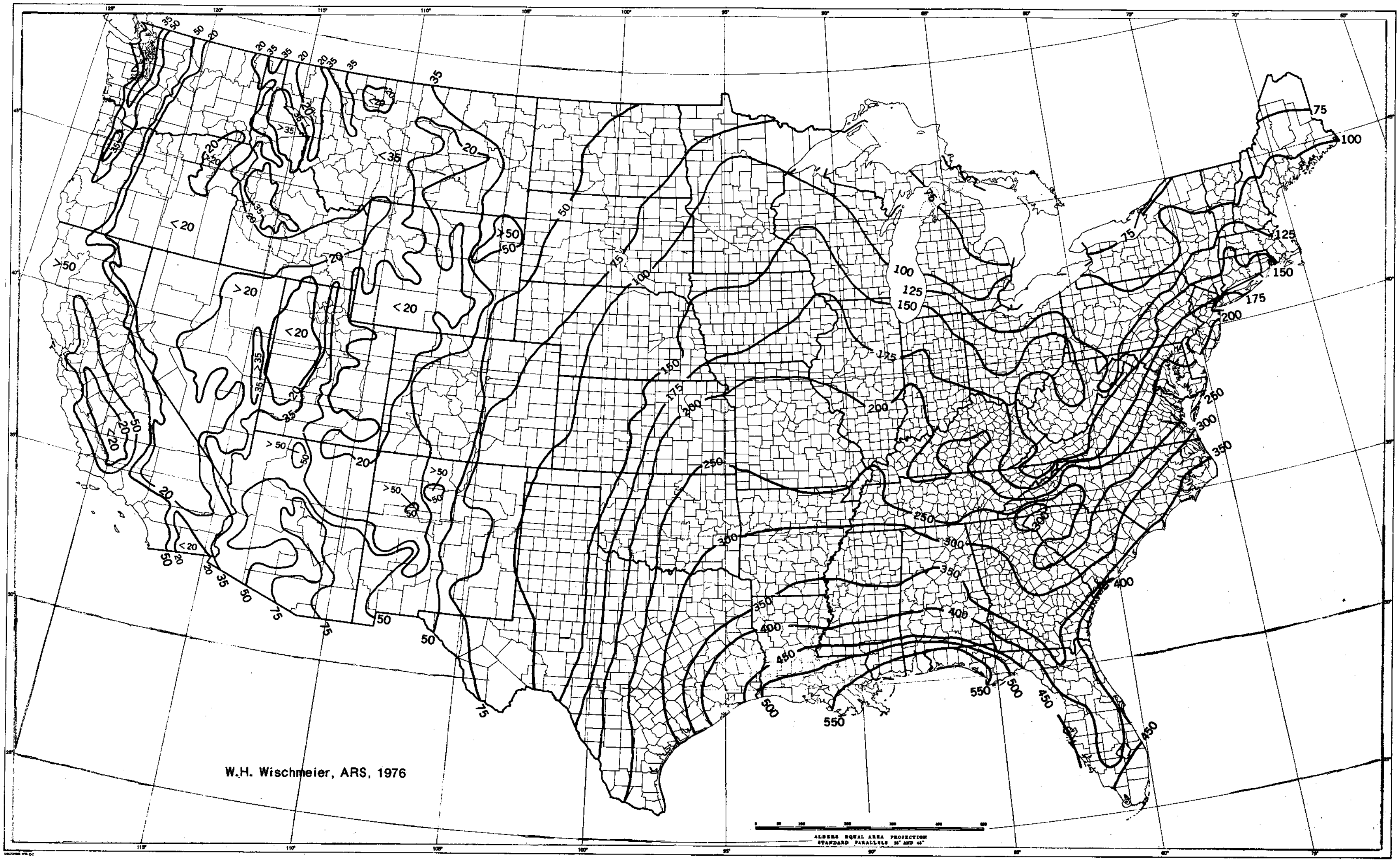
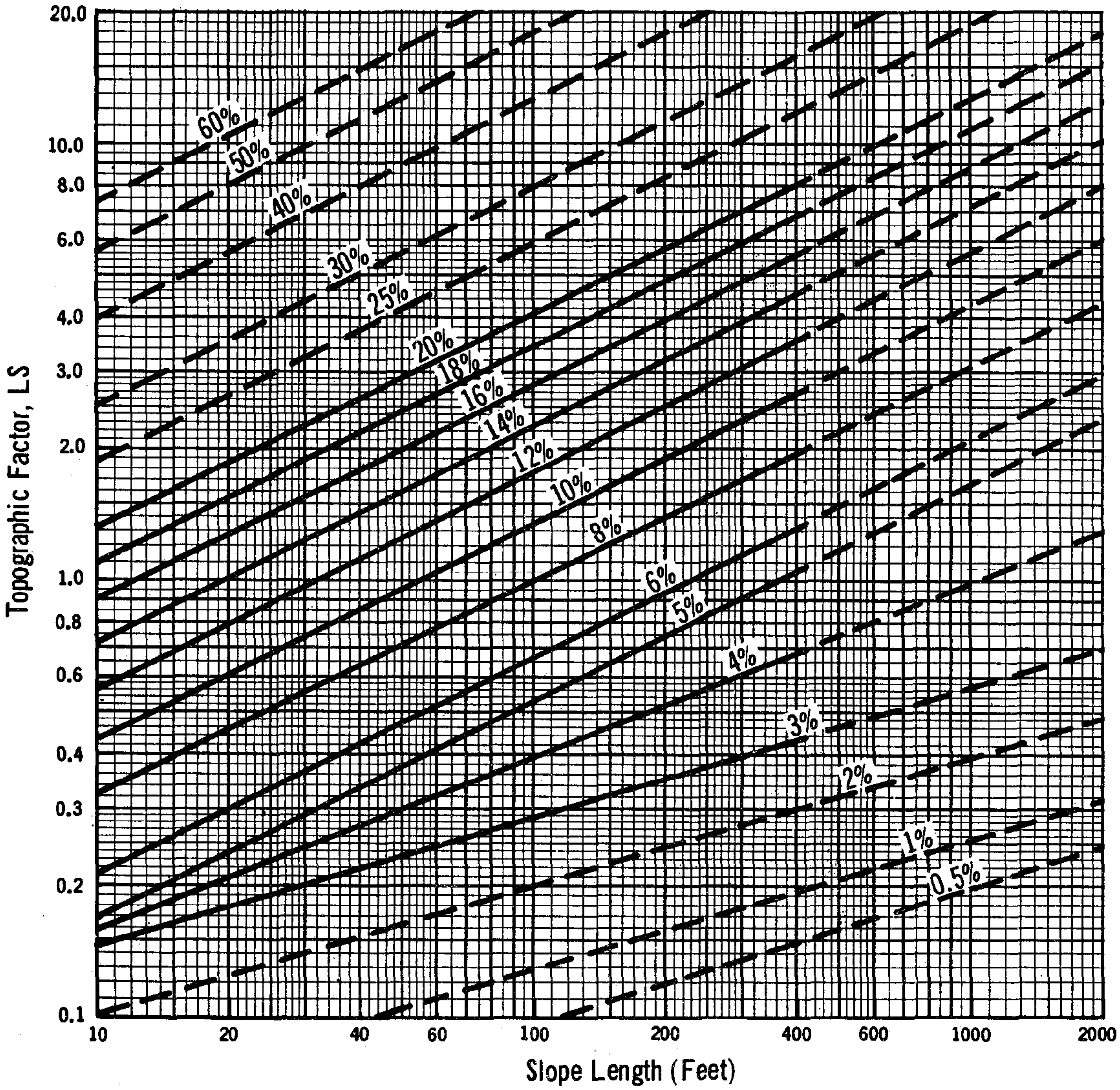


Figure 3-1.—Average annual values of the R factor.



*The dashed lines represent estimates for slope dimensions beyond the range of lengths and steepnesses for which data are available. The curves were derived by the formula:

$$LS = \left(\frac{\lambda}{72.6}\right)^m \left(\frac{430x^2 + 30x + 0.43}{6.57415}\right)$$

where λ = field slope length in feet and m = 0.5 if s = 5% or greater, 0.4 if s = 4%, and 0.3 if s = 3% or less; and x = sin θ. θ is the angle of slope in degrees.

Figure 3-2.—Slope-effect chart (topographic factor, LS).

Table 3–1.—Values of the topographic factor, LS for specific combinations of slope length and steepness[1]

Percent slope	Slope length (feet) 25	50	75	100	150	200	300	400	500	600	800	1,000
0.2	0.060	0.069	0.075	0.080	0.086	0.092	0.099	0.105	0.110	0.114	0.121	0.126
0.5	.073	.083	.090	.096	.104	.110	.119	.126	.132	.137	.145	.152
0.8	.086	.098	.107	.113	.123	.130	.141	.149	.156	.162	.171	.179
2	.133	.163	.185	.201	.227	.248	.280	.305	.326	.344	.376	.402
3	.190	.233	.264	.287	.325	.354	.400	.437	.466	.492	.536	.573
4	.230	.303	.357	.400	.471	.528	.621	.697	.762	.820	.920	1.01
5	.268	.379	.464	.536	.656	.758	.928	1.07	1.20	1.31	1.52	1.69
6	.336	.476	.583	.673	.824	.952	1.17	1.35	1.50	1.65	1.90	2.13
8	.496	.701	.859	.992	1.21	1.41	1.72	1.98	2.22	2.43	2.81	3.14
10	.685	.968	1.19	1.37	1.68	1.94	2.37	2.74	3.06	3.36	3.87	4.33
12	.903	1.28	1.56	1.80	2.21	2.55	3.13	3.61	4.04	4.42	5.11	5.71
14	1.15	1.62	1.99	2.30	2.81	3.25	3.98	4.59	5.13	5.62	6.49	7.26
16	1.42	2.01	2.46	2.84	3.48	4.01	4.92	5.68	6.35	6.95	8.03	8.98
18	1.72	2.43	2.97	3.43	4.21	4.86	5.95	6.87	7.68	8.41	9.71	10.9
20	2.04	2.88	3.53	4.08	5.00	5.77	7.07	8.16	9.12	10.0	11.5	12.9

[1]$LS = (\lambda/72.6)^m (65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065)$ where λ = slope length in feet; m = 0.2 for gradients <1 percent, 0.3 for 1- to 3-percent slopes, 0.4 for 3.5- to 4.5-percent slopes, 0.5 for 5-percent slopes and steeper; and θ = angle of slope. (For other combinations of length and gradient, interpolate between adjacent values.)

as low as 0.0001 for woodland with a 100-percent duff cover. Values of the C factor for undisturbed forest land are given in table 3–3. Table 3–4 gives values for forest land that has been harvested and cropland that has been converted to woodland, both of which required some mechanical preparation for planting.

Tables 3–2, 3–3, and 3–4 provide a wide range of values for the C factor. Although some land situations may not fit neatly in any of the three general categories, a representative C factor for most situations can be obtained from these tables.

Erosion Control Practice Factor (P)

The P factor measures the effect of control practices that reduce the erosion potential of the runoff by their influence on drainage patterns, runoff concentration, and runoff velocity. Practices for which P factors have been established are contouring and contour stripcropping. The latter values are also used for contour-irrigated furrows. In contour stripcropping, strips of sod or meadow are alternated with strips of row crops or small grains. Terraces and diversions, where used, reduce the length of slope. The P values for computing sediment yield reduction for terraces and diversions are given in table 3–5.

Water Quality and Sediment Yield

The computed soil loss for large areas is not sediment yield, and it is not directly related to water quality. Overland sediment transport is a complex process of transport and deposition. The USLE estimates the transport component and specifically excludes the deposition component. For example, only 5 percent of the computed soil loss may appear as sediment yield in a drainage area of 500 mi^2. The remaining 95 percent is redistributed and deposited on uplands or flood plains and is not a net soil loss from the area. Procedures for computing sediment yield are given in Chapter 6.

Example of Use of USLE in Watershed Planning

Assume a watershed area of 600 acres above a proposed floodwater-retarding structure in Fountain County, Ind. (fig. 3–3). Compute the average annual soil loss from sheet erosion for present conditions and that for future conditions after the recommended land treatment has been applied on all land in the watershed.

Present conditions.—Cropland: 280 acres of continuous corn with residue removed, cultivated upslope and downslope, average yield of 70 bu/acre; soil is Fayette silt loam; slopes are 8 percent and 200 ft long.

Table 3-2.—C factors for permanent pasture, grazed forest land, range, and idle land[1]

Vegetative canopy		Cover that contacts the soil surface						
			Percent ground cover					
Type and height[2]	Percent cover[3]	Type[4]	0	20	40	60	80	95+
No appreciable canopy		G	0.45	0.20	0.10	0.042	0.013	0.003
		W	.45	.24	.15	.091	.043	.011
Tall grass, weeds, or short brush with average drop fall height of 20 in. or less	25	G	.36	.17	.09	.038	.013	.003
		W	.36	.20	.13	.083	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.076	.039	.011
	75	G	.17	.10	.06	.032	.011	.003
		W	.17	.12	.09	.068	.038	.011
Appreciable brush or bushes, with average drop fall height of 6½ ft	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.087	.042	.011
	50	G	.34	.16	.08	.038	.012	.003
		W	.34	.19	.13	.082	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.078	.040	.011
Trees, but no appreciable low brush. Average drop fall height of 13 ft	25	G	.42	.19	.10	.041	.013	.003
		W	.42	.23	.14	.089	.042	.011
	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.087	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.084	.041	.011

[1]The listed C values require that the vegetation and mulch are randomly distributed over the entire area. For grazed forest land multiply these values by 0.7.
[2]Canopy height is measured as the average fall height of water drops falling from the canopy to the ground. Canopy effect is inversely proportional to drop fall height and is negligible if fall height exceeds 33 ft.
[3]Portion of total-area surface that would be hidden from view by canopy in a vertical projection (a bird's-eye view).
[4]G: cover at surface is grass, grasslike plants, decaying compacted duff, or litter. W: cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral-root network near the surface) or undecayed residues or both.

R = 185
K = 0.37
LS = 1.4
C = 0.43
P = 1.00

A (annual soil loss) = $185 \times 0.37 \times 1.4 \times 0.43 \times 1.0$
= 41.2 tons/acre

Pasture: 170 acres; 50 percent of area has canopy cover of short brush (0.5-m [1.6-ft] fall height); 80 percent of surface is covered by grass and grasslike plants; soil is Fayette silt loam; slopes are 8 percent and 200 ft long.

R = 185
K = 0.37
LS = 1.4
C = 0.012

A (annual soil loss) = $185 \times 0.37 \times 1.4 \times 0.012$
= 1.15 tons/acre

Forest: 150 acres; 30 percent of area has tree; canopy; 50 percent of surface is covered by litter; undergrowth is unmanaged; soil is Bates silt loam; slopes are 12 percent and 100 ft long.

$$R = 185$$
$$K = 0.32$$
$$LS = 1.8$$
$$C = 0.009$$

$$A \text{ (annual soil loss)} = 185 \times 0.32 \times 1.8 \times 0.009 = 0.96 \text{ ton/acre}$$

Future conditions.—Cropland: 280 acres in rotation of wheat, meadow, corn, corn with residue left, contour stripcropped; soil is Fayette silt loam;

Table 3-3.—C factors for undisturbed forest land[1]

Percentage of area covered by canopy of trees and undergrowth	Percentage of area covered by duff[2]	C factor[3]
100–75	100–90	0.0001–0.001
70–45	85–75	.002 - .004
40–20	70–40	.003 - .009

[1]Where effective litter cover is less than 40 percent or canopy cover is less than 20 percent, use table 3-2. Also use table 3-2 where woodlands are being grazed, harvested, or burned.

[2]Percentage of area covered by duff is dominant. Interpolate on basis of duff, not canopy.

[3]The ranges in listed C values are caused by the ranges in the specified forest litter and canopy covers and by variations in effective canopy heights.

Table 3-4.—C factors for mechanically prepared woodland sites

Site preparation	Mulch cover[1]	Soil condition[2] and weed cover[3]							
		Excellent		Good		Fair		Poor	
		NC	WC	NC	WC	NC	WC	NC	WC
	Percent								
Disked, raked, or bedded[4]	None	0.52	0.20	0.72	0.27	0.85	0.32	0.94	0.36
	10	.33	.15	.46	.20	.54	.24	.60	.26
	20	.24	.12	.34	.17	.40	.20	.44	.22
	40	.17	.11	.23	.14	.27	.17	.30	.19
	60	.11	.08	.15	.11	.18	.14	.20	.15
	80	.05	.04	.07	.06	.09	.08	.10	.09
Burned[5]	None	.25	.10	.26	.10	.31	.12	.45	.17
	10	.23	.10	.24	.10	.26	.11	.36	.16
	20	.19	.10	.19	.10	.21	.11	.27	.14
	40	.14	.09	.14	.09	.15	.09	.17	.11
	60	.08	.06	.09	.07	.10	.08	.11	.08
	80	.04	.04	.05	.04	.05	.04	.06	.05
Drum chopped[5]	None	.16	.07	.17	.07	.20	.08	.29	.11
	10	.15	.07	.16	.07	.17	.08	.23	.10
	20	.12	.06	.12	.06	.14	.07	.18	.09
	40	.09	.06	.09	.06	.10	.06	.11	.07
	60	.06	.05	.06	.05	.07	.05	.07	.05
	80	.03	.03	.03	.03	.03	.03	.04	.04

[1]Percentage of surface covered by residue in contact with the soil.

[2]*Excellent* soil condition—Highly stable soil aggregates in topsoil with fine tree roots and litter mixed in. *Good*—Moderately stable soil aggregates in topsoil or highly stable aggregates in subsoil (topsoil removed during raking), only traces of litter mixed in. *Fair*—Highly unstable soil aggregates in topsoil or moderately stable aggregates in subsoil, no litter mixed in. *Poor*—No topsoil, highly erodible soil aggregates in subsoil, no litter mixed in.

[3]NC—No live vegetation. WC—75-percent cover of grass and weeds having an average drop fall height of 20 in. For intermediate percentages of cover, interpolate between columns.

[4]Modify the listed C values as follows to account for effects of surface roughness and aging. *First year after treatment*: multiply listed C values by 0.40 for rough surface (depressions >6 in.); by 0.65 for moderately rough; and by 0.90 for smooth depressions <2 in.) *For 1 to 4 years after treatment*: multiply listed factors by 0.7. *For 4+ to 8 years*: use table 3-2. *More than 8 years*: use table 3-3.

[5]*For first 3 years*: use C values as listed. *For 3+ to 8 years after treatment*: use table 3-2. *More than 8 years after treatment*: use table 3-3.

slopes are 8 percent and 200 ft long.

$$
\begin{aligned}
R &= 185 \\
K &= 0.37 \\
LS &= 1.4 \\
C &= 0.119 \\
P &= 0.3
\end{aligned}
$$

$$
\begin{aligned}
A \text{ (annual soil loss)} &= 185 \times 0.37 \times 1.4 \times 0.119 \\
&\quad \times 0.3 \\
&= 3.4 \text{ tons/acre}
\end{aligned}
$$

Pasture: 170 acres with improved management; 25 percent of area has canopy cover (4-m [13-m] fall height); ground cover in an area not protected by canopy is increased to 95 percent; soil is Fayette silt loam; slopes are 8 percent and 200 ft long.

$$
\begin{aligned}
R &= 185 \\
K &= 0.37 \\
LS &= 1.4 \\
C &= 0.003 \\
P &= 0.3
\end{aligned}
$$

$$
\begin{aligned}
A \text{ (annual soil loss)} &= 185 \times 0.37 \times 1.4 \times 0.003 \\
&= 0.29 \text{ ton/acre}
\end{aligned}
$$

Forest: 150 acres with improved management; canopy cover increased to 60 percent; litter cover increased to 80 percent; soil is Bates silt loam; slopes are 12 percent and 100 ft long.

$$
\begin{aligned}
R &= 185 \\
K &= 0.32 \\
LS &= 1.8 \\
C &= 0.003
\end{aligned}
$$

$$
\begin{aligned}
A \text{ (annual soil loss)} &= 185 \times 0.32 \times 1.8 \times 0.003 \\
&= 0.32 \text{ ton/acre}
\end{aligned}
$$

Summary of average annual soil loss.—Present conditions:

Cropland:	280 acres × 41.2 tons/acre	=	11,536 tons/year
Pasture:	170 acres × 1.15 tons/acre	=	196 tons/year
Forest:	150 acres × 0.96 ton/acre	=	144 tons/year

Future conditions:

Cropland:	280 acres × 3.4 tons/acre	=	952 tons/year
Pasture:	170 acres × 0.29 ton/acre	=	49 tons/year
Forest:	150 acres × 0.32 ton/acre	=	48 tons/year

Table 3-5.—P values for contour-farmed terraced fields[1]

	Farm planning		Computing sediment yield[2]	
Land slope (percent)	Contour factor[3]	Stripcrop factor	Graded channels, sod outlets	Steep backslope, underground outlets
1 to 2	0.60	0.30	0.12	0.05
3 to 8	.50	.25	.10	.05
9 to 12	.60	.30	.12	.05
13 to 16	.70	.35	.14	.05
17 to 20	.80	.40	.16	.06
21 to 25	.90	.45	.18	.06

[1]Slope length is the horizontal terrace interval. The listed values are for contour farming. No additional contouring factor is used in the computation.
[2]These values include entrapment efficiency and are used for control of offsite sediment within limits and for estimating the field's contribution to watershed sediment yield.
[3]Use these values for control of interterrace erosion within specified soil-loss tolerances.

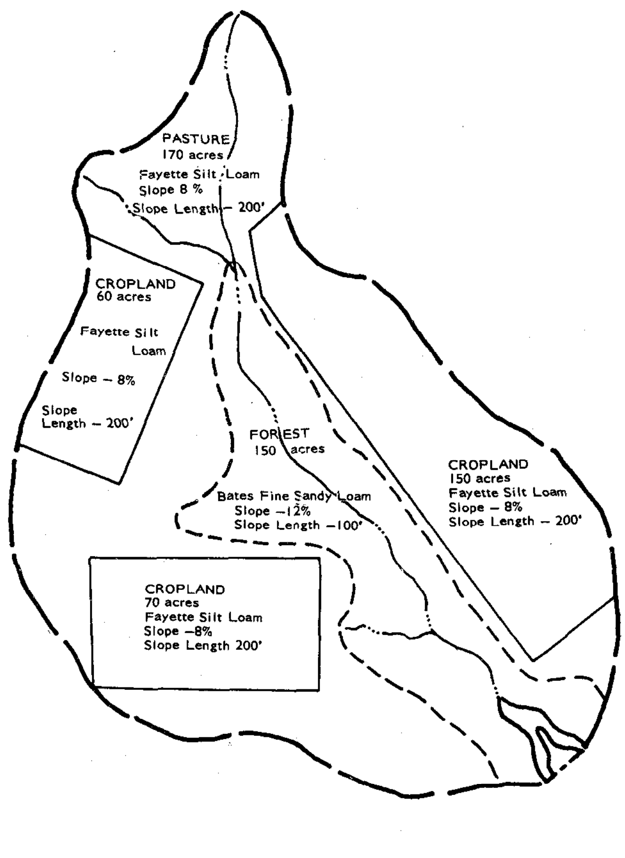


Figure 3-3.—Hypothetical 600-acre watershed used in example.

Enter these values on Form SCS-ENG-309 (Rev. 1974) and follow the procedure set forth in Chapter 8, Sediment-Storage Design Criteria, to obtain the sediment yield at the proposed floodwater-retarding structure.

Channel Erosion

Channel erosion consists of the removal of soil and rock by a concentrated flow of water. Concentrated flow permits a more concerted local attack on the soil and associated materials. Channel erosion includes gully erosion, streambank erosion, streambed degradation, flood-plain scour, valley trenching, and much roadbank erosion.

Factors Involved

Gullies usually follow sheet erosion. They begin in a slight surface depression into which, in time, the concentrated flow cuts a channel a foot or more deep. The shape of the channel is usually determined by the relative resistance of the soil.

Streambank erosion and bed degradation are affected primarily by the bank materials and the resistance of the channel bottom to the character and direction of flow. Removal of the natural vegetation from streambanks increases bank erosion. The presence of coarse bed material that a stream cannot pick up during reduced flows results in an attack on the banks by the flowing water.

When estimating long-term streambank erosion, keep in mind that bank erosion is a natural process and occurs even on streams that tend to maintain a long-term constant width. On these streams, bank erosion is offset by less obvious deposition and accretion. Therefore, streams of this type are not primary sources of sediment.

Streambed erosion is not a significant long-term sediment source because the material subject to this type of erosion is limited in both extent and volume. Compared with other potential sources of sediment, streambed erosion usually is minor.

Flood-plain scour is the removal of flood-plain soil by flows sweeping across the flood plain. It may occur in the form of channelization or sheet removal of the surface soil. This form of sheet erosion cannot be computed by the USLE or similar equations.

Computation Procedures

Methods of determining soil loss by the various types of channel erosion are: (1) comparing aerial photographs of different dates to determine the annual growth rate of channels; (2) rerunning existing cross sections to determine the difference in total channel cross-sectional area; (3) assembling historical data to determine the average age of channels and their average annual growth; and (4) making field studies to estimate the average annual growth rate (volume per unit length of channel).

Formulas for computing annual channel erosion from data obtained in these determinations are:

For bank erosion

$$S = H \times L \times R$$

where

S = annual soil loss from streambank erosion (cubic feet).
H = average height of bank (feet).
L = length of bank being eroded, each side of channel (feet).
R = annual rate of bank recession (feet).

Example: If H = 5 ft, L = 1,800 ft, and R = 0.1 ft,[1]

$$S = 5 \text{ ft} \times 1{,}800 \text{ ft} \times 0.1 \text{ ft} = 900 \text{ ft}^3$$

For channel degradation

$$S = W \times L \times R$$

where

S = volume voided by channel degradation (cubic feet).
W = average bottom width of channel (feet).
L = length of channel bottom being eroded (feet).
R = annual rate of degradation (feet).

Example: If W = 20 ft, L = 900 ft, and R = 0.2 ft,[2]

$$S = 20 \text{ ft} \times 900 \text{ ft} \times 0.2 \text{ ft} = 3{,}600 \text{ ft}^3$$

---

[1] *Annual recession rates of more than 0.1 ft are common on the outside of bends and meanders. This cut-bank recession is usually offset by sediment accretion on the opposite slip-off slope, which results in channel migration with no substantial change in channel width. Significant long-term changes in channel width cannot occur without equally drastic changes in discharge, slope, or depth.*

[2] *An annual degradation rate of 0.2 ft for 100 years (normal project life) would deepen the channel by 20 ft. This rate is not likely to occur in a perennial stream.*

Figure 3–4 is a nomograph that can be used to estimate the volume of material lost annually because of various types of channel erosion. A procedure for calculating gully erosion is presented in more detail in Technical Release No. 32 (Soil Conservation Service 1966).

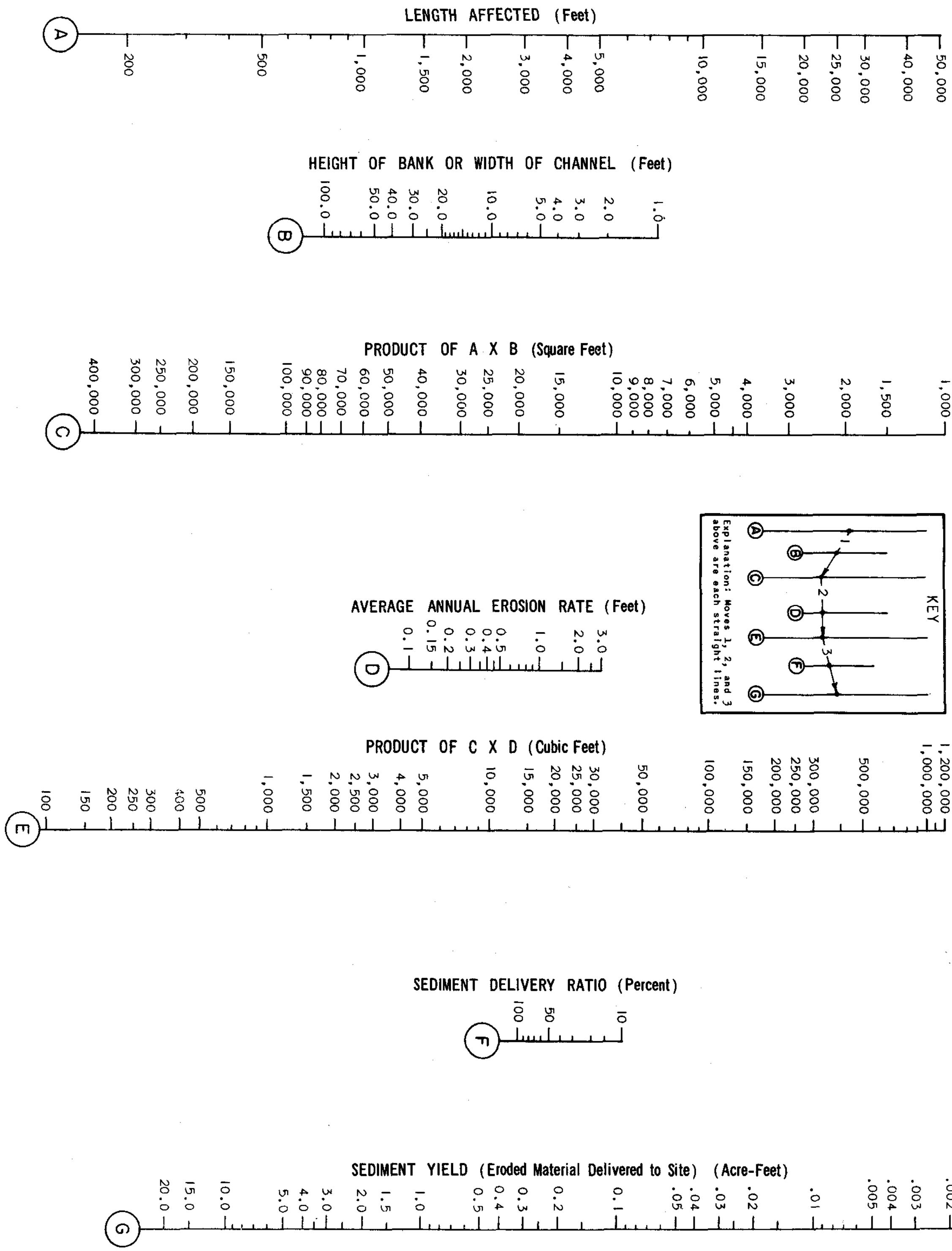


Figure 3–4.—Nomograph for computing average annual gully erosion, streambank erosion, channel entrenchment, and flood-plain scour in acre-feet.

Wind erosion is the detachment and transport of soil material by wind. The process is called deflation, and the resultant deposits are classified as eolian. The rate of erosion depends on the intensity and persistence of the wind, size and availability of soil particles, and amount of protective cover. Dry soil is necessary for maximum deflation rates.

In the United States, the conditions generally most favorable for wind erosion are in semiarid or arid areas west of the 100th meridian, although wind erosion does occur elsewhere. Although water erosion is dominant even in arid areas, wind erosion can approach it in amount in deserts and during periods of intensive drought in other areas.

Eolian deposits are characterized by highly sorted particles, by cross-bedded or lenticular structures, and by dunes oriented by the prevailing winds. A hummocky surface develops when wind-blown sediment lodges around isolated bushes or grass. Fence-line deposits are confined to the area alongside the fence and can be several feet thick.

Deflation areas contain scoured-out depressions or pock-marked surfaces. Such features are usually in exposed places and are not associated with water drainage rills or channels. Remnants of grass or even single pebbles may rest on small pedestals in the eroded zone. Some shrubs or bunches of grass may persist with the root system exposed above ground. In gravelly sands, selective removal of the smaller particles can produce a gravel pavement on the surface.

The amount of deflation can be determined by comparing the voided area with the original ground surface. Measure enough cross sections to delineate an average-sized depression and determine the number of depressions on recent aerial photographs or count the number per unit area.

Wind-deposited materials may have come from outside a watershed. Conversely, a watershed under study may have lost much soil to distant areas. Windblown sediment moves progressively in the direction of the prevailing winds rather than downslope.

The most important aspect of wind erosion to be considered in studies of sediment yield is the deposition of windblown sediment in channels from which it is easily flushed and added to the sediment yield of the watershed. Channels act as natural traps for airborne sediment whether they contain water or not. If eolian deposition in channels is a factor in the watershed being studied, measure the annual volume of deposition. A sampling process will usually be adequate. Unless channel capacity is decreasing because of these deposits, add the volume of these sediments to the sediment yield. The sediment delivery ratio depends on the kind of material. Wind erosion does not occur every year in most areas. Adjust the annual sediment yield rates downward to account for years in which wind erosion does not occur.

In some areas a significant amount of windblown soil may be deposited on snow. During snowmelt the soil is carried by water into streams or drainage ditches. This snow-caught sediment can be measured by pushing metal tubes into the snow and weighing the contents after the snow in the sample melts.

Many factors affect the amount of soil moved by wind erosion. An equation has been developed (Chepil and Woodruff 1963) to predict the average annual soil loss from wind erosion:

$$E = f(I, C, K, L, V)$$

where

E = average annual soil loss (tons per acre).
I = annual soil erodibility (tons per acre).
C = local wind-erosion climatic factor (percent).
K = soil surface roughness (ratio).
L = equivalent width of field (feet).
V = equivalent quantity of vegetal cover (proportionate factor).

Soil erodibility (I) is determined from the percentage of the nonerodible soil fraction greater than 0.84 mm in diameter (Chepil 1962). The local wind-erosion climatic factor (C) is estimated from a wind-erosion climatic map developed by Chepil, Siddoway, and Armbrust (1962). Surface soil roughness (K) is measured in terms of the height of standard ridges spaced at right angles to the wind, with a height-spacing ratio of 1 to 4. The equivalent width of the field (L) is the unsheltered distance along the prevailing wind-erosion direction. The equivalent quantity of vegetation (V) is a proportionate factor determined by the quantity, type, and orientation of the vegetal cover. Instructions for use of these factors, as well as maps, charts, and tables, are in Agriculture Handbook 346 (Agricultural Research Service 1968).

Mass movement includes slumps, mud flows, soil and rock falls, rotational and planar slides, avalanches, and soil creep. Unlike wind and water, mass movement does not carry soil or rock out of the general region in which it formed, but mass movement is often an important factor in soil removal. It can increase or decrease erosion from one source, change a stream channel regime, and alter the drainage area of a watershed.

Factors Involved

Mass movement occurs when shear stress exceeds shear strength. High shear stress can be caused by removal of lateral support; added weight of rain, snow, or talus accumulations; construction or other human activities; transitory earth stresses, such as earthquakes; regional tilting; removal of underlying support; and lateral pressure from water in cracks and caverns, freezing of water, or swelling of clay or anhydrite (Highway Research Board 1958).

Low shear strength can be caused by:

1. Composition. Inherently weak materials such as saturated clay and silt are examples.
2. Texture, such as loose arrangement of particles or roundness of grains.
3. Gross structure, including discontinuities from faults, bedding planes, or joints, or strata inclined toward a free face.
4. Changes resulting from weathering and other physiochemical reactions.
5. Changes in intergranular forces resulting from pore water.
6. Changes in internal structure, such as fissuring in preconsolidated clays or the effect of disturbance or remolding on sensitive materials (Highway Research Board 1958).

Gravity is, of course, the main force in these mass movements. Usually, landslides are precipitated by some combination of the factors listed above. No movement can occur, however, unless the topographic conditions help to create the instability.

Estimation Procedures

No standard procedures for calculating erosion by mass movement have been developed; it must therefore be estimated.

Numerous measurements have been made in the semiarid West to determine the maximum angles at which slopes stand with and without vegetal cover. Nonvegetated talus material stands at gradients between 68 and 80 percent (angles of about 34 to 38 degrees). Vegetated slopes underlain by fine-textured soils derived from the same parent material as the barren talus stand at gradients of as much as 173 percent (angle of 60 degrees). Without vegetation, slopes of fine material would not stand, even at gradients as high as those of coarse talus (Bailey 1941).

The hazard of debris flows can be estimated on the basis of slope. These flows usually originate on slopes of more than 30 percent. The terminal slope of debris flows is between 7 and 10 percent.

A procedure for calculating erosion from mass movement would require measuring the volume of materials moved. For large masses, comparing the findings of a topographic survey of the mass with the original topography (from standard quadrangle sheets if available) provides an estimate of the volume of materials moved. For smaller masses, a grid of hand-auger borings extending into the original soil profile can provide a basis for estimating the volume.

Other types of erosion not described in detail here do occur and must be evaluated if found in areas under study.

Wave Erosion

Caused by wind and water, wave erosion is an important source of sediment along shorelines of oceans, lakes, and rivers. Wave erosion can change shorelines markedly and can be measured in many places (Jones and Rogers 1952, Glymph and Jones 1937). The rate of erosion from wave action can be measured by comparing two sets of aerial photographs taken on different dates, as in estimating channel erosion. Historical data form another basis for estimating wave erosion rates. Unless the shoreline was mechanically shaped during reservoir construction, wave erosion along a reservoir shore can also be determined by comparing the present shore profile with an extrapolation of the slope of the profile above the influence of wave action (fig. 3–5.).

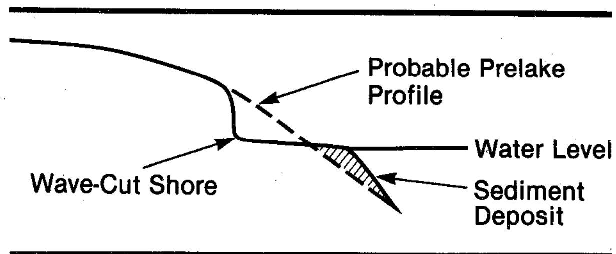


Figure 3–5.—Projecting lines of undisturbed bank to determine probable prelake profile.

Erosion from Strip Mining and Construction

Strip mining or excavating operations and construction of highways, industrial areas, public buildings, housing, shopping centers, and related areas greatly accelerate erosion of exposures and spoil banks. Each condition must be evaluated as a separate problem.

Holeman and Geiger (1959) estimated that the Lake Barcroft, Va., watershed yielded 25 acre-ft of sediment in 1951, when 9 percent of the area (13 mi^2) was under construction, an increase of 21.3 acre-ft over the pre-1938 average annual rate of 3.7 acre-ft. The sediment yield was 16.3 acre-ft/mi^2 for the area under construction and 0.257 acre-ft/mi^2 for the watershed in the earlier period of agricultural use. Before 1938, 18 percent of the watershed was cultivated, 23.5 percent in pasture, 53 percent in woods, and 5.5 percent residential. Construction activities are believed to have increased the sediment yield to more than 63 times the pre-1938 level.

Wolman and Schick (1967) found that the sediment yield in construction areas averaged 72 times that in rural areas. Collier et al. (1964) found that in 1959 a watershed near Somerset, Ky., with 6 percent of its area strip mined, yielded 69 times more sediment than a similar adjacent watershed that was wooded and unmined.

These findings do not mean that areas under construction always yield 70 times the sediment that they would under rural conditions, but the figures do indicate the general size of the increase. In areas undergoing urbanization, the average annual amount of soil exposed can be estimated from such factors as population curves and the number of sewer connections, to determine annual trends.

The USLE is the most promising method for calculating erosion on construction sites or strip-mined areas, but appropriate values for factors of the equation must be carefully selected. Keep in mind that the soil surface is probably not in the same condition as it would be under any agricultural use. The microrelief and soil surface conditions are likely to vary much more over short distances than they do in any agricultural situation. The USLE K values are indexed to "tilled continuous fallow" and a specific microrelief and surface texture that may not be common on construction sites. Topsoil K values are currently determined by use of a nomograph (Wischmeier, Johnson, and Cross 1971). Recent research (Roth, Nelson, and Romkins 1974) indicates that factors other than those considered by Wischmeier et al. may be significant in determining the erodibility of exposed cohesive subsoil.

Sediment yield from construction sites and strip-mined areas can be estimated from the computed erosion and a sediment delivery ratio. Consider projected erosion-control measures realistically when determining the sediment delivery ratio.

Ice Erosion

In watersheds likely to be studied in the SCS small watershed program, erosion by ice probably falls into one of three categories: (1) glacial gouging around the margin of mountain glaciers, (2) erosion by ice along river channels during spring freshets, and (3) erosion by ice shoved along the shores of northern lakes. Ice erosion usually is not an important source of sediment.

References

Agricultural Research Service, U.S. Department of Agriculture. 1961. A universal equation for measuring wind erosion. Agric. Res. Serv. Spec. Rep. 22–69, 20 p.

Bailey, R. W. 1941. Land erosion—normal and accellerated—in the semiarid West. Am. Geophys. Union Trans. 22 (pt. 2):240–261.

Bennett, H. H. 1939. Soil conservation. McGraw-Hill Book Co., New York, 993 p.

Chepil, W. S. 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. Soil Sci. Soc. Am Proc. 26(1):4–6.

Chepil, W. S., and N. P. Woodruff. 1963. The physics of wind erosion and its control. Adv. Agron. 15:211–302.

Chepil. W. S., F. H. Siddoway, and D. V. Armbrust. 1962. Climatic factor for estimating wind erodibility of farm fields. J. Soil Water Conserv. 17(4):162–165.

Collier, C. R., et al. 1964. Influence of strip mining on the hydrologic environment of parts of Beaver Creek Basin, Kentucky, 1955–59. U.S. Geol. Surv. Prof. Pap. 427–B, 85 p.

Dissemeyer, G. E., and G. R. Foster. 1980. A guide for predicting sheet and rill erosion on forest land. USDA For. Serv. Tech. Publ. SA–TP.

Ellison, W.D. 1945. Some effects of raindrops and surface flow on soil erosion and infiltration. Am. Geophys. Union Trans. 26(pt. 3):415–429.

Glymph, L. M., Jr., and V. H. Jones. 1937. Advance report on the sedimentation survey of Lake Decatur, Decatur, Illinois. USDA Soil Conserv. Serv. SCS–SS–12, 23 p.

Highway Research Board, National Research Council. 1958. Landslides and engineering practice. Highway Res. Board Spec. Rep. 29, NAS–NRC Publ. 544, 232 p.

Holeman, J. N., and A. F. Geiger. 1959. Sedimentation of Lake Barcroft, Fairfax County, Va. USDA Soil Conserv. Serv. Tech. Publ. 136, 16 p.

Horton, R. E. 1941. Discussion of "Sheet-erosion—present and past." Am. Geophys. Union Trans. 22 (pt. 2):299–305.

Jones, Victor H., and Ross E. Rogers. 1952. Aspects of sedimentation in Lake Waco, Waco, Texas. USDA Soil Conserv. Serv. Tech. Pap. 100.

Musgrave, G. W. 1947. The quantitative evaluation of factors in water erosion—a first approximation. J. Soil Water Conserv. 2(3):133–138.

Roehl, J. W. 1965. Erosion and its control on agricultural land. Fed. Inter-Agency Sediment. Conf. 1963 Proc. U.S. Dep. Agric. Misc. Publ. 970, p. 18–22.

Roth, C., D. Nelson, and M. J. M. Romkins. 1974. Alternate criteria for determining subsoil "K" values. U.S. Environmental Protection Agency.

Skidmore, E. L., and N. P. Woodruff. 1968. Wind erosion forces in the United States and their use in predicting soil loss. USDA Agric. Res. Serv. Agric. Handbk. 346, 42 p.

Soil Conservation Service, U.S. Department of Agriculture. 1966. Procedure for determining rates of land damage, land depreciation, and volume of sediment produced by gully erosion. Engineering Division Tech. Release No. 32, Geology.

United Nations. 1953. The sediment problem. Flood Control Ser. No. 5. Economic Commission for Asia and the Far East, Bangkok.

Wischmeier, W. H. 1974. New developments in estimating water erosion. 29th Ann. Meeting of the Soil Conserv. Soc. Am. Proc., Syracuse, N.Y., Aug. 11–14, p. 179–186.

Wischmeier, W. H. 1976. Use and misuse of the universal soil loss equation. J. Soil Water Conserv. 31:5–9.

Wischmeier, W. H., and D. D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. U.S. Dep. Agric., Agric. Handb. 282, 47 p.

Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion losses. A guide to conservation planning. U.S. Dep. Agric., Agric. Handb. 537, 58 p.

Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil Water Conserv. 26:189–193.

Wolman, M. G. 1964. Problems posed by sediment derived from construction activities in Maryland. Md. Water Pollution Control Comm. Rep., 125 p.

Wolman, M. G., and A. P. Schick. 1967. Effects of construction on fluvial sediment, urban and suburban areas of Maryland. Am. Geophys. Union. Water Resour. Res. 3(2):451–464.

United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Chapter 4

Transmission of Sediment by Water

Contents

	Page
Symbols	4-1
Terms	4-3
General	4-4
Factors affecting sediment transport	4-4
Characteristics of water as the transporting medium	4-4
Laminar sublayer	4-4
Characteristics of transportable materials	4-5
Mechanism of entrainment	4-5
Forces acting on discrete particles	4-5
Tractive force	4-5
Determining critical tractive stress	4-6
Determining critical velocity	4-6
Hydraulic considerations	4-8
Fixed boundaries	4-8
Movable boundaries	4-8
Movement of bed material	4-9
Schoklitsch formula	4-10
Meyer-Peter formula	4-10
Haywood formula	4-11
Meyer-Peter and Muller formula	4-11
Einstein bedload function	4-11
Engelund-Hansen procedure	4-12
Colby procedure for relating mean velocity to sand transport	4-15
Using the graphs to determine the discharge of sands	4-15
Application and limitations of formulas	4-18
Comparison of predictive methods	4-20
Example of a channel problem	4-24
Summary of procedures for evaluation of bed material transport problems	4-27
Transport of suspended sediment	4-29
Suspension mechanism	4-29
Sampling and laboratory procedures	4-29
Sediment-rating curve and flow-duration curve method of computing suspended-sediment load	4-31
References	4-35
Appendix	4-36

Figures

Page

4–1a Critical shear stress for quartz sediment in water as a function of grain size 4-7
4–1b Critical water velocity for quartz sediment as a function of mean grain size.................... 4-8
4–2 Sediment load classification 4-9
4–3 Relationship between grain roughness (τ') and form drag (τ'') and total bed shear (τ_0)........... 4-12
4–4 Relationship between dimensionless forms of bed shear (θ and θ')............................... 4-13
4–5 Graphical solution to $\frac{q}{\sqrt{(S_s - 1)gd^3}}$ and ϕ in the Engelund-Hansen procedure 4-14
4–6 Relationship of discharge of sands to mean velocity for six median sizes of bed sand, four depths of flow, and a water temperature of 60° F 4-16
4–7 Approximate correction factors for the effect of water temperature and concentration of fine sediment (4–7a) and sediment size (4–7b) on the relationship of discharge of sands to mean velocity .. 4-17
4–8 Characteristics of bed material 4-18
4–9 Sediment rating curves for Mountain Creek near Greenville, S.C., according to several formulas compared with measurements 4-21
4–10 Sediment rating curves for Niobrara River near Cody, Nebr., according to several formulas compared with measurements 4-22
4–11 Sediment rating curves for Colorado River at Taylor's Ferry, Ariz., according to several formulas compared with measurements 4-23
4–12 Vertical distribution of sediment in Missouri River at Kansas City, Mo. 4-30
4–13 Sediment rating curve, Cottonwood Creek, any State 4-32
4–14 Flow-duration curve, Cottonwood Creek, any State 4-33
4–15 Form-drag friction factor in sand-bed channels, f''_b, as a function of R_b/d_{50} and $F_D = \frac{U}{\sqrt{gd_{50}}}$ 4-38
4–16 Friction-factor predictor for flat-bed flows in alluvial channels 4-39
4–17 Depth-discharge relationships obtained by Alam-Kennedy technique 4-39

Tables

Page

4–1 Discharge data for example channel problem, high flow 4-24
4–2 Sediment transport computed for various flows 4-25
4–3 Discharge data for example channel problem, lower flow 4-25
4–4 Sediment transport computed for lower flows 4-26
4–5 Checklist of procedures for solving bed-material transport problems 4-28
4–6 Factor A for computing sediment in milligrams per liter by Equation 4-6 4-31
4–7 Computation of average annual suspended-sediment load, Cottonwood Creek, any State 4-34

Chapter 4
Transport of Sediment by Water

Symbols

Symbol	Description	Unit
A	Area of flow, cross section	Feet
b	Channel width or water surface width	Feet
D	Depth of flow	Feet
d_{50}	Median size of sediment (letter d with numerical subscript denotes particle size in sediment for which the percentage by weight corresponding to subscript is finer, e.g., d_{84} is size for which 84 percent of sediment by weight is finer).	Millimeters, inches, or feet
d_m	Effective diameter of the bed material	Feet or millimeters
d_s	Particle size (unspecified)	Millimeters, inches, or feet
F_n or F_d	Froude number; equal to $\frac{U}{(gD)^{1/2}}$	Dimensionless
f	Darcy-Weisbach friction coefficient $\frac{8gRS}{U^2}$	Dimensionless
g	Acceleration due to gravity, 32.2 *or* 9.8	Feet per second per second *or* Meters per second per second
k_s	Representative grain size	Feet
Q	Water discharge	Cubic feet per second
Q_b	Bedload discharge	Tons per day or pounds per second
Q_s	Water discharge effective in transporting bedload	Cubic feet per second
Q_T	Total bed-material discharge	Tons per day or pounds per second
q	Unit water discharge	Cubic feet per second per foot of channel width
q_o or q_c	Unit water discharge just sufficient to move bed material	Cubic feet per second per foot channel width

q_B	Unit bedload discharge	Tons per day per foot or pounds per second per foot of channel width
q_T	Unit bed-material discharge	Tons per day per foot or pounds per second per foot of channel width
R	Hydraulic radius	Feet
R_b	Hydraulic radius with respect to the bed	Feet
R_N or R_e	Reynolds number; equal to $\frac{UD}{\nu}$ or $\frac{4UR}{\nu}$	Dimensionless
R_*	Boundary Reynolds number; equal to $\frac{U_* d_s}{\nu}$ (Shields)	Dimensionless
R'	Hydraulic radius with respect to the grain	Feet
R''	Hydraulic radius with respect to dunes and bars	Feet
S	Slope	Feet per foot
S_w	Water surface slope or hydraulic gradient	Feet per foot
S_o	Bed slope	Feet per foot
S_e	Energy gradient	Feet per foot
S_s	Specific gravity of sediment	Dimensionless
T°	Water temperature	Degrees Fahrenheit or degrees Celsius
u_*	Shear velocity $(gDS_e)^{1/2}$	Feet per second
u'_*	Shear velocity associated with grain roughness	Feet per second
U or V	Mean velocity	Feet per second
w	Fall velocity of sediment particles	Feet per second
γ	Unit weight of water, 62.4 *or* 1.0	Pounds per cubic foot *or* Grams per cubic centimeter
γ_s	Unit weight of sediment, dry	Pounds per cubic foot
Δ_γ	Difference between the specific weight of sediment and that of water	Pounds per cubic foot
δ	Thickness of laminar sublayer	Feet
θ	A form of the bed shear, τ_o	Dimensionless
ν	Kinematic viscosity	Square feet per second
μ	Dynamic viscosity	Pound-seconds per square foot
ϱ	Density of water	Slugs per cubic foot
ϱ_s	Density of sediment	Slugs per cubic foot
Ψ	A parameter indicating the ability of a flow to dislodge a given particle size (Einstein)	Dimensionless
Φ	A parameter describing the intensity of transport of bed material in a given size range (Einstein)	Dimensionless
τ_o	Total bed shear stress	Pounds per square foot
τ_c	Critical tractive stress associated with beginning of bed movement (Shields)	Pounds per square foot
τ'	Shear stress associated with grain resistance	Pounds per square foot
τ''	Shear stress associated with irregularities in bed and banks	Pounds per square foot

Antidunes. Bed forms that occur if the water velocity is higher than that forming dunes and plane beds. Antidunes commonly move upstream and are accompanied by and in phase with waves on the water surface.
Armor. A layer of particles, usually gravel size, that covers the bed as a coarse residue after erosion of the finer bed materials.
Bed form. Generic term used to describe a sand streambed. Includes ripples, dunes, plane bed, and antidunes (see fig. 4–3).
Bedload. Material moving on or near the streambed by rolling, sliding, and making brief excursions into the flow a few diameters above the bed.
Bed-material load. The part of the total load of a stream that is composed of particle sizes present in appreciable quantities in the shifting parts of the streambed.
Coefficient of viscosity. The ratio of shear stress to the velocity gradient perpendicular to the direction of flow of a Newtonian fluid or the ratio of shear stress in a moving liquid to the rate of deformation.
Coefficient of kinematic viscosity. The ratio of the coefficient of viscosity to the density of a fluid.
Dunes. Bed forms with a triangular profile having a gentle upstream slope. Dunes advance downstream as sediment moves up the upstream slope and is deposited on the steeper downstream slope. Dunes move downstream much more slowly than the stream flow.
Fall diameter or standard fall diameter. The diameter of a sphere that has a specific gravity of 2.65 and the same terminal velocity as a particle of any specific gravity when each is allowed to settle alone in quiescent distilled water of infinite extent and at a temperature of 24° C. A particle reaches terminal velocity when the water resistance is equal to the force of gravity.
Laminar flow. Low-velocity flow in which layers of fluid slip over contiguous layers without appreciable mixing.
Plane bed. A sedimentary bed with irregularities no larger than the maximum size of the bed material.
Ripples. Bed forms that have a triangular profile and are similar to dunes but much smaller.
Standing waves. Water waves that are in phase with antidunes.
Suspended load. The part of the total sediment load that moves above the bed layer. The weight of suspended particles is continuously supported by the fluid (see wash load).
Turbulent flow. A state of flow in which the fluid is agitated by crosscurrents and eddies.
Uniform flow. A flow in which the velocity is the same in both magnitude and direction from point to point along a reach.
Wash load. The part of the sediment load of a stream composed of fine particles (usually smaller than 0.062 mm) found only in relatively small quantities in the streambed. Almost all the wash load is carried in nearly permanent suspension, and its magnitude depends primarily on the amount of fine material available to the stream from sources other than the bed.

Understanding the principles of sediment transport by flowing water is essential to interpreting and solving many problems. The individual characteristics of water and sediment and their interaction directly affect the type and volume of material eroded and transported and the place and time of deposition. Evaluating channel instability, including erosion or aggradation, and predicting the performance of proposed channel improvements are problems that require knowledge of sediment transport and use of procedures pertaining to it. Information derived from following sediment-transport prediction procedures is used in determining requirements for storage of coarse sediment in debris basins and other types of structures.

This chapter includes a discussion of the characteristics of water as a medium for initiating the movement and transport of sediment. The reaction of material on the streambed to the hydraulic forces exerted and the effect of velocity and flow depth on the rate of bed-material transport are described. Formulas and procedures designed to predict the rate of bed-material transport are given and evaluated. Recommendations are made for applying these formulas and procedures to channel problems. The chapter concludes with a discussion of the mechanism of suspended-load transport and a description of a method for computing suspended-load yield from concentration and flow-duration data.

The mechanism of entrainment and the rate at which sediment is transported depend on the characteristics of the transporting medium and on the properties and availability of particles.

Characteristics of Water as the Transporting Medium

The interrelated characteristics of water that govern its ability to entrain and move sedimentary particles are density, viscosity, and acidity.

Density is the ratio of mass to volume. Increasing the temperature of water increases its volume and decreases its density. With an increase in temperature from 40 to 100° C (104 to 212° F), water will expand to 1.04 times its original volume. In working with large volumes of moving water, the slight variations in density that result from temperature change are usually ignored.

Viscosity is the cohesive force between particles of a fluid that causes the fluid to resist a relative sliding motion of particles. Under ordinary pressure, viscosity varies only with temperature. A decrease in water temperature from 26.7 to 4.4° C (80 to 40° F) increases viscosity about 80 percent.

Changes in viscosity affect the fall velocity of suspended sediment and thereby its vertical distribution in turbulent flow (Colby and Scott 1965, p. 62). Increasing the viscosity lowers the fall velocity of particles, particularly very fine sands and silts.

A substantial decrease in water temperature and the consequent increase in viscosity smooth the bed configuration, lower the Manning "n" roughness coefficient, and increase the velocity over a sand bed (U.S. Department of the Army 1968).

The pH value is the negative logarithm (base 10) of the hydrogen-ion concentration. Neutral water has a pH value of 7.0. Acid water has a pH value lower than 7.0; alkaline water has a pH value higher than 7.0.

In acid waters sediment deposition may be promoted by the formation of colloidal masses of very fine sediments (flocculation) that settle faster than their component fine particles.

Laminar Sublayer

In turbulent flow, a thin layer forms adjacent to the bed in which the flow is laminar because the fluid particles in contact with the bed do not move. This is the laminar sublayer; the higher the velocity or the lower the viscosity, the thinner the sublayer. If the boundary is rough enough, its irregularities may project into the theoretical laminar sublayer, thereby preventing its actual development.

Although laminar flow is primarily related to fluid viscosity, turbulent flow is affected by a number of factors. In laminar flow, filaments of water follow parallel paths, but in turbulent flow, the paths of particles crisscross and touch, mixing the liquid. A criterion defining the transition from laminar to turbulent flow is the Reynolds number, R_e—a ratio of inertial force to shear force on the fluid particle. If the Reynolds number is low, shear forces are dominant, but as the Reynolds number increases, they decline to little significance, thereby indicating the dominance of inertial forces.

The association of laminar flow with viscosity and that of turbulent flow with inertia are the same whether the fluid is moving or at rest. A small particle of sediment, such as very fine sand, settling in still or flowing water moves slowly enough to sustain laminar flow lines in relatively viscous media. Inertial forces become increasingly important as grain size increases and are dominant when the particle size exceeds 0.5 mm.

Characteristics of Transportable Materials

The characteristics of discrete particles are discussed in Chapter 2. The entrainment and transport of granular materials depend on the size, shape, and specific weight of the particles and their position with respect to each other. The resistance of cohesive materials depends largely on the forces of interparticle bonding. Cohesive forces can be attributed to several factors, including the amount and kind of clay minerals, the degree of consolidation or cementation, and the structure of the soil mass.

Forces Acting on Discrete Particles

Turbulence is a highly irregular motion characterized by the presence of eddies. The degree to which eddies form depends on the boundary roughness and geometry of the channel, and eddies are sustained by energy supplied by the flow. The eddies penetrate the laminar sublayer formed along the bed. Discrete particles resting on the bed are acted on by two components of the forces associated with the flow. One component force is exerted parallel to the flow (drag force) and the other is perpendicular to the flow (lifting force). Drag force results from the difference in pressure between the front and the back sides of a particle. Lifting force results from the difference in pressure on the upper and lower surfaces. If the lifting force exceeds the particle's immersed weight and the interference of neighboring grains, the particle goes into suspension.

Because turbulence is random and irregular, discrete particles tend to move in a series of short, intermittent bursts. In each burst, particles move a short distance and many grains move simultaneously. Then the movement subsides until another burst occurs. The frequency and extent of movement increases with the intensity of turbulence, and above a certain intensity some particles may be projected into the flow as suspended load (Sutherland 1967). The coarser and rounder the particles, however, the greater the possibility that they will begin to roll and continue rolling.

Tractive Force

Experiments to determine the forces that act on particles on a streambed were performed mainly to predict channel stability. More advanced methods are necessary to describe transport.

The instantaneous interactions between turbulent flow and discrete sediment particles resting on the bed were described briefly in the preceding paragraphs. In practical application, however, it is more convenient to deal with time-average values of the force field generated by the flow near the bed. Here, the forces normal to the bed having a time average equal to zero can be eliminated and only those forces parallel to the bed need to be considered. The time average of these forces is the tractive force. The tractive force measured over a unit surface area is the tractive stress. In a prismatic channel reach of uniform flow bounded by two end sections, the mean value of tractive stress is equal to the weight of the water prism in the reach multiplied by the energy gradient and divided by the wetted boundary surface in the reach. Shear stress or force per unit area of bed is expressed as $\tau_0 = \gamma R\ S_e$.

Determining Critical Tractive Stress

The most widely used and most reliable evaluation of tractive stress related to the initiation of motion is that developed by Shields (1936). The theoretical concepts, supported by experiments, resulted in a plot of $\dfrac{\tau_c}{\gamma(\frac{\gamma_s}{\gamma} - 1)d_s}$ against $\dfrac{U_* d_s}{\nu}$. The first expression is an entrainment function and the second is the boundary Reynolds number, indicating the intensity of flow turbulence around the particle. The Shields data are based on particles of uniform size and a flat bed. The Shields experiments indicate that beyond a certain value of the boundary Reynolds number, $\dfrac{U_* d_s}{\nu}$, the value of the parameter $\dfrac{\tau_c}{\gamma(\frac{\gamma_s}{\gamma} - 1)d_s}$ remains constant. Within these limits, the critical tractive stress is therefore proportional to grain size.

Data on critical tractive stresses obtained in a number of investigations were assembled by Lane (1955). These data show that the critical tractive stress in pounds per square foot is equal to $\tau_c = 0.5\ d_{75}$, where d_{75} is the size in inches of the bank material at which 25 percent by weight is larger. The limiting (allowable) tractive stress was determined from observations of canals (Lane 1955). The recommended limiting tractive stress in pounds per square foot is equal to 0.4 of the d_{75} size in inches for particles that exceed 0.25 in diameter. Results of experiments on finer particles vary considerably, probably because of variations in experimental conditions. These include differences in interpreting the initiation of sediment movement, in temperature of the water, in concentration of colloids, and in configuration of the bed. Critical conditions for initiating movement sometimes are determined by the number of particles or the frequency with which the particles start to move. For example, one observer's criterion is the time at which particles begin to move every 2 seconds at a given spot on the bed (Sutherland 1967).

In figure 4–1a the critical tractive (shear) stress is plotted against the mean particle size or to the d_{75}. The figure shows the differences in critical tractive stress resulting from temperature variation and the boundary Reynolds number at various tractive stress levels. The wide departure of Lane's curve for critical tractive stress from the others in figure 4–1a is believed to be due to Lane's use of the data of Fortier and Scobey (1926) from canals after aging. The stability of some soils is increased by aging.

Determining Critical Velocity

Determining the critical velocity (the velocity at which particles in the bed begin to move) is another method for establishing stability criteria. Figure 4–1b shows critical water velocity as a function of mean grain size. There has been less agreement on critical velocity than on critical tractive stress, probably because bottom velocity increases more slowly with increasing depth than does mean velocity. Critical conditions for initiating movement can be expressed directly in terms of tractive stress, but critical mean velocity must be related to variation in velocity with depth.

Determining the correct critical value for tractive stress or velocity is important when considering stability problems in channels in which there is to be no significant movement of the boundary material. The significance of the critical value is determined by the magnitude and duration of flows that initiate sediment movement. A prolonged flow slightly exceeding the critical value may have little significance in terms of the volume of bed material transported. On the other hand, a brief flow substantially exceeding the critical value could transport a large volume of sediment.

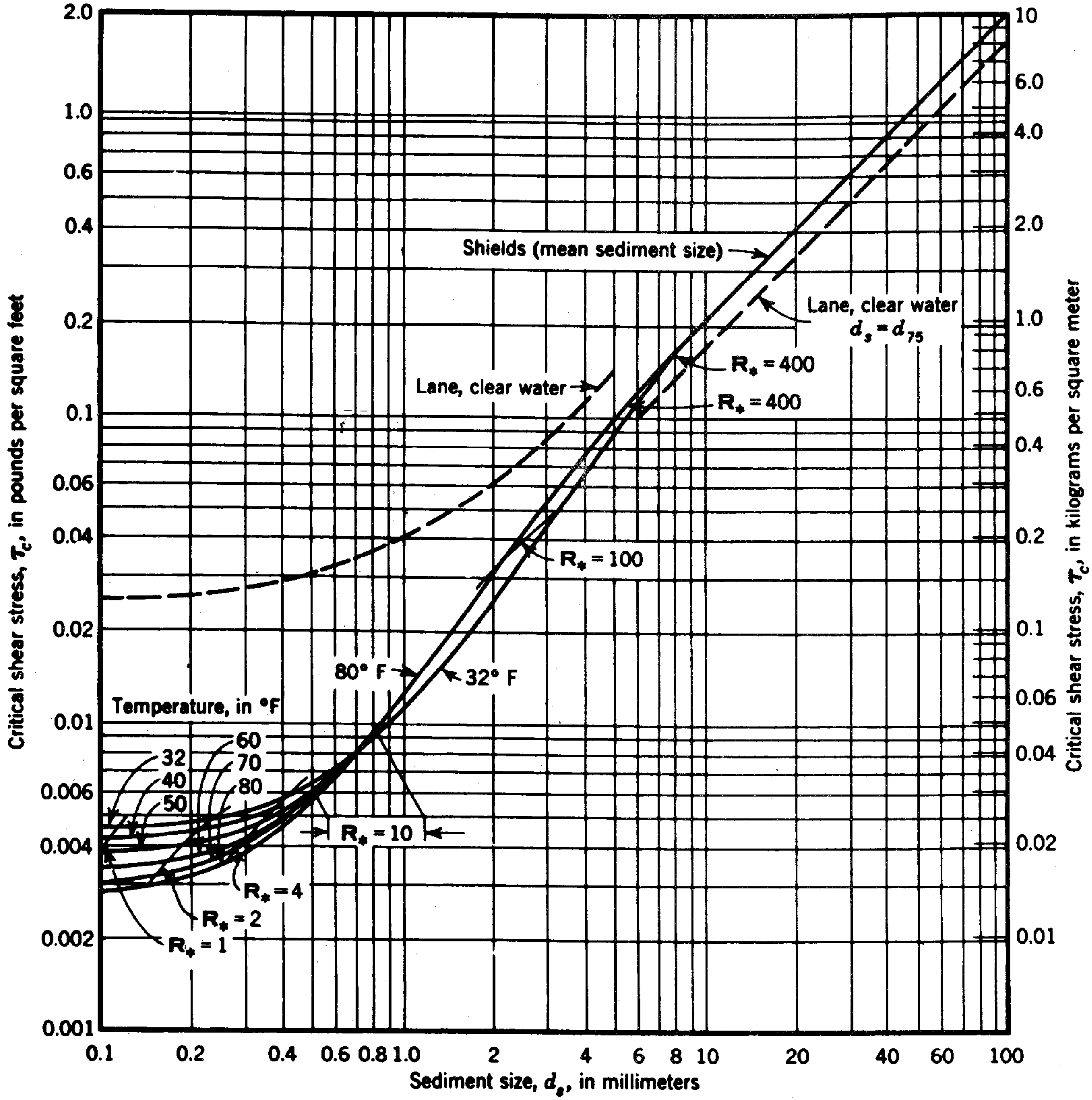


Figure 4–1a.—Critical shear stress for quartz sediment in water as a function of grain size. From Shields (1936), Lane (1955), and American Society of Civil Engineers (1975, p. 99).

Fixed Boundaries

The relationships of velocity, stage, and discharge for stream channels with fixed boundaries have long been satisfactorily predicted by selecting the appropriate "n" value in Manning's and other related formulas.

Movable Boundaries

Study of the hydraulics of movable boundaries has been directed to two general problems. Primary interest has been in determining methods for predicting the friction coefficient and thereby the correct velocity, stage, and discharge relationships for channel design. The need for these data as a key element in predicting sediment transport has added incentive to the investigations. The changes in bed form produced on a movable bed and the consequent change in friction characteristics of the bed have therefore become one of the most intensively studied flow phenomena. The literature on this subject generally describes the sequence of changes in bed configuration that can occur as the flow and transport intensity increase.

Ripples, ripples on dunes, or dunes may form at a low transport rate, and antidunes or a flat bed may form at a high transport rate. These bed forms have been observed in sand-bed flumes and streams with a d_{50} size finer than 1.0 mm. The variety of bed forms in coarser material seems to be smaller.

Pioneering efforts in investigating the hydraulics of movable beds led to dividing the hydraulic radius into two parts. One part is the radius resulting from the roughness of the grain size of the individual particles (R′), and the other is the radius resulting from the roughness of the bed configuration (R″) (Einstein 1950; Einstein and Barbarossa 1952).

From field observations Einstein and Barbarossa developed a graph relating the dimensionless ratio $\frac{V}{U''_*}$ (where $U''_* = (gR''S_e)^{1/2}$) to Einstein's flow-intensity parameter, Ψ. This graph indicates that for a given set of conditions it is possible to develop a unique stage-discharge relationship and thus to predict the hydraulics of a channel with movable boundaries. Vanoni and Brooks (1957) presented a graphical solution to the friction equation from which R′ is determined.

Another procedure for predicting hydraulic behavior in movable channel beds is based on the division of slope, S, into two parts, S′ and S″ (Meyer-Peter and Muller 1948). In this procedure S′ is the energy gradient associated with the grain size of the bed material under a certain velocity and depth, excluding form resistance, and S″ is the additional gradient pertaining to bed-form resistance. This division of slope was adopted by Alam and Kennedy (1969), whose procedure is explained in the appendix to this chapter.

A similar hydraulic consideration sometimes used as part of the preliminary procedure in sediment

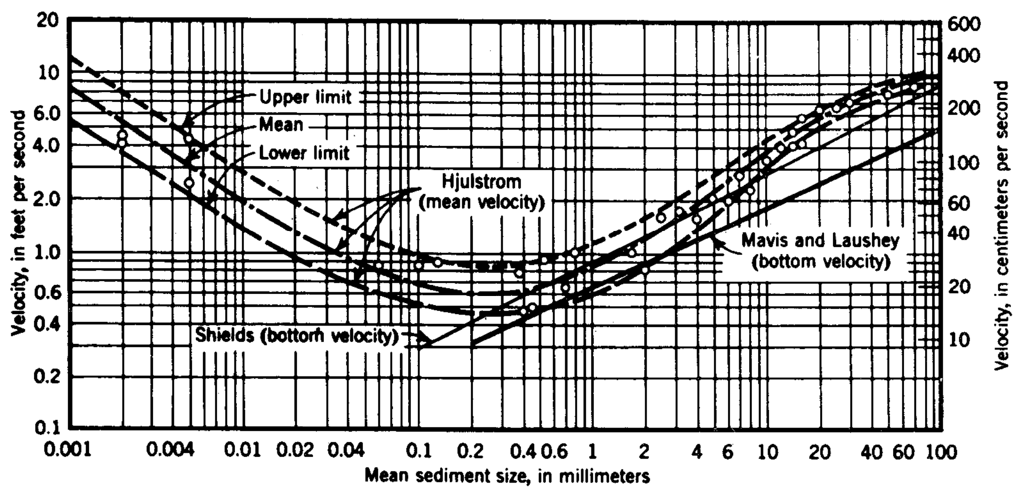


Figure 4–1b.—Critical water velocity for quartz sediment as a function of mean grain size. From American Society of Civil Engineers (1975, p. 102).

transport computations is the treatment of bank friction as completely distinct from bed friction. One such approach, involving use of Manning's friction equation, is included as part of the procedure in the Einstein bedload function.

In this discussion the term "bed-material load" is defined as that part of the total sediment load (suspended load plus bedload) that is composed of grain sizes occurring in appreciable quantities in the bed material. The part of the total load that consists of grain sizes not present in the bed material in significant quantities is the wash load. Sand-size particles that constitute all or the major part of the bed material travel either on the bed as bedload or in suspension. Figure 4–2 illustrates how the total sediment load is classified—bedload, bed-material load, and wash load. Evaluation techniques are not refined enough to predict accurately what part of the bed-material load moves in suspension or what part moves as bedload under specific hydraulic conditions. Establishing this separation does not seem essential to the general solution of sediment transport problems.

Transport rates for sand and gravel have been determined by both direct measurement and computation. Measurements of the transport rate in natural streams have been few, chiefly because of the difficulty in getting representative measurements. Sampling equipment established in or on the bed tends to alter the direction of flow filaments and the sediment concentration. The more accurate measurements have been made by using equipment installed to withdraw representative samples of the water-sediment mixture during specific periods. Another method is to sample the total load as the flow moves over a sill at an elevation the same as that of the slope upstream.

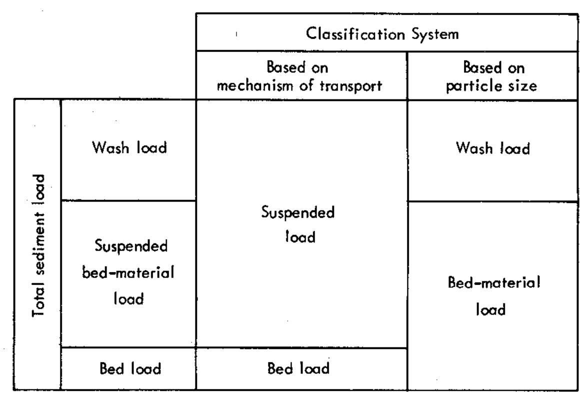


Figure 4–2.—Sediment load classification. Adapted from Cooper and Peterson (1970, p. 1,881).

The existence of many procedures for predicting transport rates indicates both the difficulty of obtaining measurements and the influence of many variables on the consistency of results. Because flume studies are the most easily controlled and exclude some variables, they have become the primary means of establishing relationships between stream discharge and bed-material load.

The earliest bed-material transport formula still in use is that of Duboys, who published results of studies of the Rhone River in 1879. Duboys originated a concept common to many later formulas when he assumed in his derivation that the rate of sediment transport is proportional to the tractive stress in excess of the critical value required to initiate motion.

The Duboys formula is

$$q_T = \Psi\tau_0 (\tau_0 - \tau_c) \qquad \textbf{(4-1)}$$

where

q_T = rate of sediment transport per unit width of stream;

Ψ = a coefficient that depends on characteristics of the sediment (not to be confused with Einstein's Ψ);

τ_c = a value established by experiment (not the same as that of Shields).

Early in the twentieth century, several flume studies of sand transport were started, including that of Shields. He is best known for developing criteria for the initiation of movement. Probably the most extensive early investigation of sediment transport in flumes was Gilbert's in about 1910 (Gilbert 1914). Descriptions of a number of transport phenomena resulted from those experiments, but no general formula was derived.

Of the formulas that follow, those of Schoklitsch, Meyer-Peter, Haywood, and Meyer-Peter and Muller are bedload formulas. The Einstein bedload function, the Engelund-Hansen procedure, and the Colby procedure determine the rate of bed-material transport, both bedload and suspension load.

Schoklitsch Formula

Schoklitsch developed one of the more extensively used empirical formulas (Shulits 1935; Shulits and Hill 1968). He used his own experimental data and also data from Gilbert's flume measurements.

The 1934 Schoklitsch formula in English units is

$$q_B = \frac{86.7}{(d_{50})^{1/2}} S_e^{3/2} (q - q_0) \qquad \textbf{(4-2)}$$

where

q_B = unit bedload discharge (pounds per second per foot of width);

d_{50} = medium size of sediment (inches);

$q_0 = 0.00532 \dfrac{d_{50}}{S_0^{\ 4/3}}$.

In describing the formula, Shulits recommended using a cross section in a straight reach of river where the depth of water is as uniform as possible and the width changes as little as possible with stage. As described by Shulits, the Schoklitsch formula fits Gilbert's measurements for uniform particle sizes of about 0.3 to 7 mm and slopes ranging from 0.006 to 0.030 ft/ft for small particles and 0.004 to 0.028 ft/ft for larger particles.

Meyer-Peter Formula

In 1934 the Laboratory for Hydraulic Research at Zurich, Switzerland, published a bedload transport formula based on flume experiments with material of uniform grain size. The original analysis of the Zurich and Gilbert data for uniform particles ranging from about 3 to 28 mm in diameter was supplemented by studies of mixtures of various-sized particles up to 10 mm and having various specific gravities.

The Meyer-Peter formula in English units is

$$q_B = (39.25\ q^{2/3}\ S_0 - 9.95\ d_m)^{3/2} \qquad \textbf{(4-3)}$$

where d_m is expressed in feet. The new term in this formula is d_m, the effective diameter of the bed material, which identifies the characteristic size of a sample. To determine this value, divide the size distribution curve of a bed-material mechanical analysis into at least 10 equal size fractions and determine the mean size and weight percentage of each fraction.

Haywood Formula

The Haywood formula is based on Gilbert's flume data and data from the U.S. Waterways Experiment Station, Vicksburg, Miss. In his evaluation, Haywood (1940) adjusted Gilbert's data to account for sidewall resistance. He assumed that the discharge effective in moving bedload is midway between the discharge of walls offering no resistance and that of walls offering the same resistance as the bed. Haywood demonstrated the close relationship of his formula to the Schoklitsch formula, which is based on some of the same data. Haywood believed that his formula substantially agrees with Scholkitsch's formula for relatively large rates of bedload movement and that it is much more accurate for very small rates of movement. Haywood considered 3 mm to be the maximum particle size for application of his formula. He regarded his formula as a modification of the Meyer-Peter formula.

The Haywood formula is

$$q_B = \left(\frac{q^{2/3} S_0 - 1.20\ d^{4/3}}{0.117\ d^{1/3}}\right)^{3/2} \qquad \textbf{(4–4)}$$

where d is d_{35} expressed in feet.

Meyer-Peter and Muller Formula

The Meyer-Peter and Muller formula is based on data obtained from continuing the experiments that resulted in the Meyer-Peter formula. The range of variables, particularly slope, was extended. A few tests were run with slopes as steep as 20 percent and sediment sizes as coarse as 30 mm. Meyer-Peter and Muller stated explicitly that their work was on bedload transport, by which they meant the movement of sediment that rolls or jumps along the bed. Transport of material in suspension is not included (Meyer-Peter and Muller 1948).

The Meyer-Peter and Muller formula as translated by Sheppard (1960) is

$$q_B = 1.606 \left[3.306 \quad \frac{Q_S}{Q} \quad \frac{d_{90}{}^{1/6\ 3/2}}{n_S} DS_e - 0.627\ d_m\right]^{3/2} \qquad \textbf{(4–5)}$$

where d_{90} and d_m are expressed in millimeters.

Nomographs are available for determining $\frac{Q_s}{Q}$ (a ratio of the discharge quantity determining bedload transport to the total discharge) and n_S (a Manning "n" value for the streambed). The formula, a significant departure from the previously cited formulas, includes a ratio of the form roughness of the bed to the grain roughness of the bed surface.

Einstein Bedload Function

In 1950 Einstein's bedload function had a major effect on investigations of the hydraulics and sediment transport characteristics of alluvial streams. Einstein (1950) described the function as "giving rates at which flows of any magnitude in a given channel will transport as bed load the individual sediment sizes of which the channel bed is composed." It was developed on the basis of experimental data, theory of turbulent flow, field data, and intuitive concepts of sediment transport.

The Einstein bedload function first computes bedload and then, by integrating the concentration at the bed layer with the normal reflection of that concentration in the remainder of the flow depth, determines the total bed-material load.

Einstein introduced several new ideas into the theory of sediment transport. Included were new methods of accounting for bed friction by dividing it into two parts, one pertaining to the sand-grain surface and the other to the bed-form roughness, such as ripples or dunes. An additional friction factor, that of the banks, is included in the procedure for determining hydraulic behavior before computing bed-material transport.

Another idea introduced by Einstein to explain the bedload function is that the statistical properties of turbulence govern the transport of particles as bedload. This statistical character is reflected in the structure of the dimensionless parameter ϕ, defined as the intensity of bedload transport. The relationship between this factor and the dimensionless flow intensity, Ψ (another dimensionless parameter reflecting the intensity of shear on the particle) is used in the procedure. The ϕ-Ψ relationship has subsequently been tested by others and found to be an appropriate determinant of bedload transport.

Engelund-Hansen Procedure

Engelund and Hansen (1967) developed a procedure for predicting stage-discharge relationships and sediment transport in alluvial streams. They introduced a parameter θ (the reciprocal of Einstein's Ψ) to represent the ratio of agitating forces (horizontal drag and lifting force) to the stabilizing force (immersed weight of the particle). This parameter is a dimensionless form of the bed shear, τ_0, to be divided into two parts: τ', the part acting directly as traction on the particle surface, and τ'', the residual part corresponding to bed-form drag. This division is similar to that of the Einstein-Barbarossa R' and R''. The authors' diagram of the relationship of bed forms to the two separations of total bed shear and to velocity is shown in figure 4–3. Principles of hydraulic similarity were used to develop a working hypothesis for describing total resistance to flow, specifically for dune-covered streambeds and bed-material discharge.

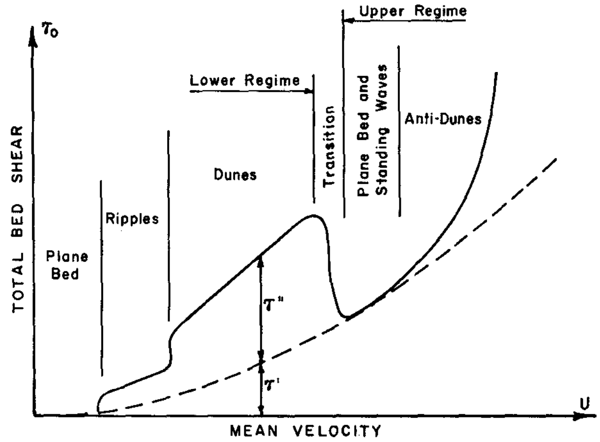


Figure 4–3.—Relationship between grain roughness (τ') and form drag (τ'') and total bed shear (τ_0). From Engelund and Hansen (1967).

The steps used in applying the Engelund-Hansen procedure are given here in some detail because the procedure demonstrates the impact of changing bed forms on bed-material transport and because it was published in a foreign journal not readily available for reference. Data from flume experiments by Guy and by Simons and Richardson (Guy, Simons, and Richardson 1966) were used to test the Engelund-Hansen theories. The mean sizes used in these experiments were 0.19, 0.27, 0.45, and 0.93 mm. Transport of the bed material, both in suspension and moving along the bed, was measured.

The Engelund-Hansen procedure includes both a simplified and a more detailed series of computations. Figure 4–4 in conjunction with figure 4–3 shows the flow regime in which a semigraphical solution, figure 4–5, applies; that is, in the region of dune formation.

The steps in applying the graphical form are as follows:

Example 1 (using the authors' symbols)

Given:

$D = 1.219$ m
d = mean fall diameter $= 3.2 \times 10^{-4}$ m
S_0 = slope of the channel $= 2.17 \times 10^{-4}$
S_s = specific gravity of sediment = 2.68

Calculate the ratio of the mean depth, D, to the mean fall diameter, d, of the bed material.

$$\frac{D}{d} = \frac{1.219}{3.2 \times 10^{-4}} = 3.81 \times 10^{3}$$

where

$$S_0 \text{ (fig. 4–5)} = 2.17 \times 10^{-4}$$

$$\left[\frac{q}{(S_s - 1)gd^3}\right]^{1/2} = 3.3 \times 10^4 \text{ and } \Phi = 1.5$$

then

$$\begin{aligned} q &= [(S_s - 1)gd^3]^{1/2}(3.3 \times 10^4) \\ &= [1.68(9.8)(3.2 \times 10^{-4})^3]^{1/2}(3.3 \times 10^4) \\ &= 0.766 \text{ m}^3/(\text{s}\cdot\text{m}) = 8.25 \text{ ft}^3/(\text{s}\cdot\text{ft}) \end{aligned}$$

and

$$\begin{aligned} q_T &= \Phi[(S_s - 1)gd^3]^{1/2} \\ &= 1.5[1.68(9.8)(3.2 \times 10^{-4})^3]^{1/2} \\ &= 3.48 \times 10^{-5}\text{m}^3/\text{s}\cdot\text{m}) \\ &= 0.000375 \text{ ft}^3/(\text{s}\cdot\text{ft}) \end{aligned}$$

At 95 lb/ft^3, sediment by weight is 95 × 0.000375 = 0.036 lb/(s·ft)

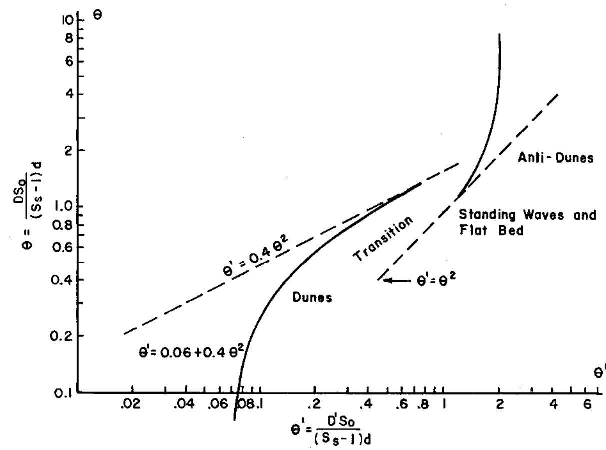


Figure 4–4.—Relationship between dimensionless forms of bed shear (θ and θ'). From Engelund and Hansen (1967) and American Society of Civil Engineers (1975, p. 135).

Example 2 shows early in the computation that the long form of computations must be followed.

Given:

D = mean depth of 1.0 ft = 0.3048 m
d = mean fall diameter of 3.2×10^{-4} m
S_s = 2.68
S_o = slope of the channel = 0.002

$$\frac{D}{d} = \frac{0.3048}{3.2 \times 10^{-4}} = 9.52 \times 10^2$$

These values fall to the right of the lined chart (fig. 4–5) and probably within the transition and plane-bed regime.

$$\theta \text{ (see figs. 4–3 and 4–4)} = \frac{DS_o}{(S_s - 1)d} \quad \frac{(0.3048)(0.002)}{(1.68)(0.00032)}$$

$$= 1.134$$

where

θ' = for transition or plane bed regime
$= 0.4\ \theta^2 = 0.514$

D' = boundary layer thickness =

$$\frac{\theta' D}{\theta} = \frac{0.514}{1.134}(0.3048)$$

$$= 0.138 \text{ m}$$

k = surface roughness as determined by Engelund-Hansen

$$= 2.5\ d = 2.5(0.32) = 0.80 \text{ mm}$$

$$\frac{U}{[gD'S_o]^{1/2}} = 6.0 + 5.75 \log \frac{D'}{k} \text{ in millimeters}$$

$$U = [9.8(0.138)(0.002)]^{1/2}$$

$$\left[6.0 + 5.75 \log \frac{138}{0.80}\right] = 0.98 \text{ m/s}$$

$$U = 3.22 \text{ ft/s}$$

$$\therefore \text{discharge} = 3.22 \text{ ft}^3/(\text{s}\cdot\text{ft})$$

The bed-material discharge can be calculated as follows:

$$f\Phi = 0.1\ \theta^{5/2}$$

(as determined by Engelund-Hansen)

where

$$f = \text{friction factor} = \frac{2g\ S_oD}{U^2}$$

$$= \frac{2(9.8)(0.002)(0.3048)}{(0.981)^2} = 0.0124$$

then

$$\Phi = \frac{0.1}{f}\theta^{5/2} = \frac{0.1}{0.0124}\ 1.134^{5/2} = 11.04$$

and

$$q_T = \Phi[(S_s - 1)gd^3]^{1/2}$$
$$= 11.04[1.68 \times 9.8(3.2 \times 10^{-4})^3]^{1/2}$$
$$= 2.564 \times 10^{-4} \text{m}^3/(\text{s}\cdot\text{m}) = 2.76 \times 10^{-3} \text{ ft}/(\text{s}\cdot\text{ft})$$

At 95 lb/ft³, sediment by weight is 0.262 lb/(s·ft).

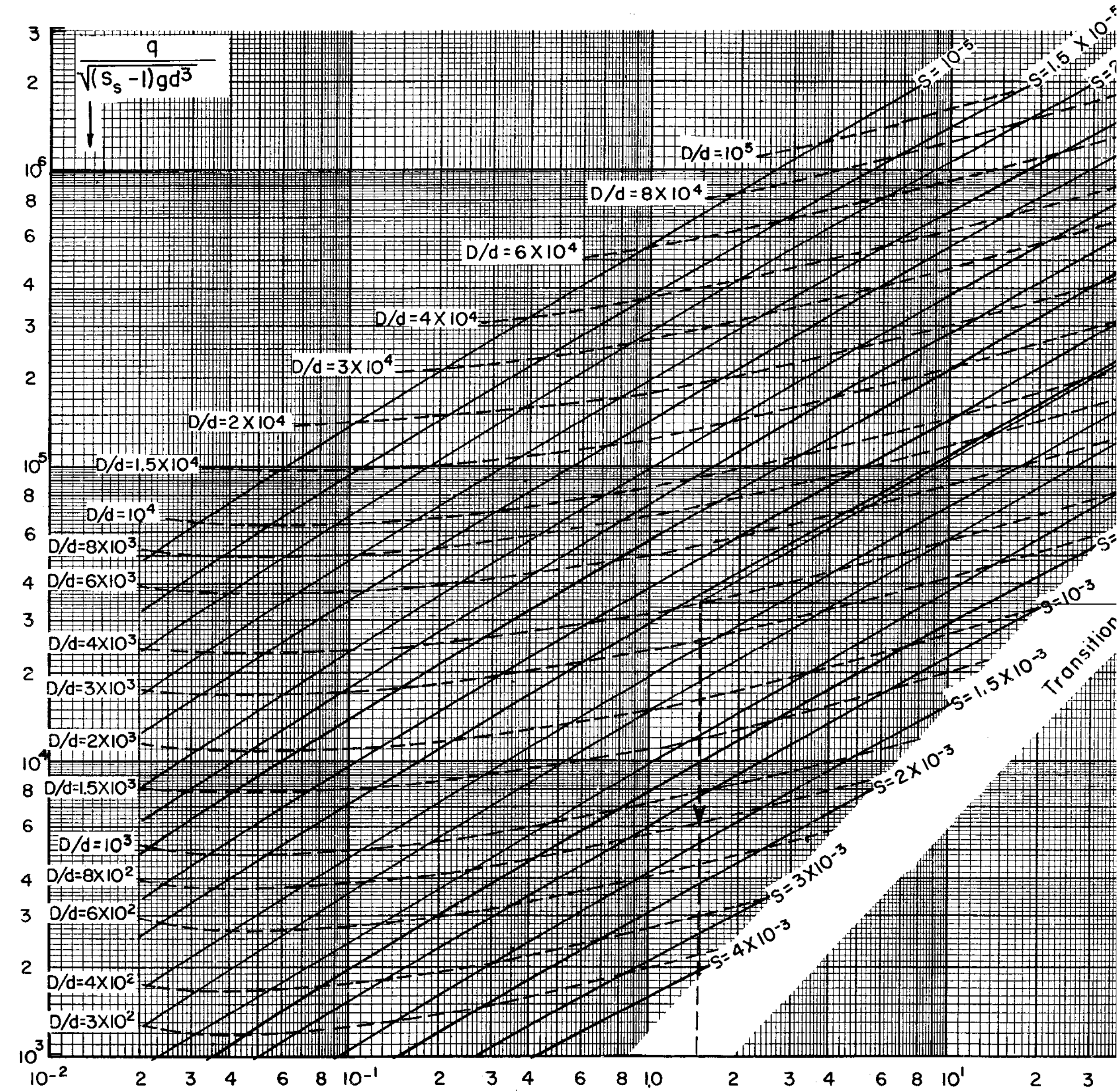


Figure 4–5.—Graphical solution to $\frac{q}{\sqrt{(S_s - 1)gd^3}}$ and ϕ in the Engelund-Hansen procedure. Adapted from Engelund and Hans American Society of Civil Engineers (1975, p. 209).

In summary, the velocity of 3.22 ft/s, discharge of 3.22 $ft^3/(s \cdot ft)$, and bed-material transport of 0.262 $lb/(s \cdot ft)$ of width are determined for a transitional or upper plane-bed regime. The Engelund-Hansen procedure does not provide a means for determining the bed-material discharge at lower flow regimes of plane beds and ripples. These regimes are not significant in terms of the volume of sediment transported.

Colby Procedure for Relating Mean Velocity to Sand Transport

The Colby procedure was developed by correlating mean velocity with sediment concentration in a sand-bed stream. The procedure, partly empirical and partly derived from Einstein's bedload function, is based on measurements in flumes and channels. The relationships are presented in figure 4–6, which gives the uncorrected sand transport as a function of velocity, depth, and the d_{50} particle size of bed material for water depths (D) of 0.1, 1, 10, and 100 ft. Each of the four sets contains curves corresponding to d_{50}'s of 0.10, 0.20, 0.30, 0.40, 0.60, and 0.80 mm.

Before the graphs in figure 4–6 can be used, velocity must be determined by observation or calculation. The bed-material load for flows with a depth other than the four values for which curves are given can be determined by reading the sand transport per foot of width (q_T) for the known velocity for the two depths indicated in figure 4-6 that bracket the desired depth. A log-log plot of D versus q_T enables interpolation of the bed-material load for the desired depth.

This bed-material load corresponds to a water temperature of 60° F and to material with negligible amounts of fine particles in suspension. The two correction factors, K_1 and K_2, in figure 4–7a compensate for the effect of water temperature and concentration of fine suspended sediment on sediment discharge if the d_{50} size of bed sediment is about 0.2 to 0.3 mm. Figure 4–7b represents an estimate of the relative effect of concentration of fine sediment or of water temperature for d_{50} sizes of bed sediment different from those in figure 4–7a. For sizes other than 0.2 and 0.3 mm, multiply the adjustment coefficients from figure 4–7a minus 1.00 by the percentages from figure 4–7b. For example, if an adjustment coefficient (K_1 or K_2) from the main diagram is 1.50 and the d_{50} size of the bed sediment is 0.5 mm, then K_3 from figure 4–7b is 60 percent of 0.5 or 30 percent. The final adjustment coefficient would be 1.30. Colby emphasized that only rough estimates can be derived from figure 4–7.

Using the Graphs to Determine the Discharge of Sands

The discharge of sands in a sand-bed stream can be computed from the graphs as follows:

Example 1, discharge of sands determined from figure 4–6.

Given

Mean velocity	=	5.8 ft/s
Depth	=	8.5 ft
d_{50} size of bed sediments	=	0.26 mm

Figure 4–6 shows that discharges of sands for the given d_{50} size are about 80 and 180 tons/(day·ft) for depths of 1 and 10 ft, respectively. Interpolation using a straightedge for the depth of 8.5 ft on a log-log plot indicates a bed-material discharge of 170 tons per day per foot of width. No corrections are required for temperature, concentration, or sediment size; therefore, the answer is 170 tons.

Example 2, discharge of sands determined from figures 4–6, 4–7a, and 4–7b.

Given

Mean velocity	=	5.8 ft/s
Depth	=	8.5 ft
d_{50} size of bed sediments	=	0.60 mm
Water temperature	=	75°F
Concentration of fine bed sediment	=	20,000 ppm

From figure 4–6, the indicated discharges of sands for the given size of 0.60 mm are about 70 and 110 tons/(day·ft) for depths of 1 and 10 ft, respectively. Interpolation indicates a sand load of 105 tons per day per foot of width for a depth of 8.5 ft. The adjustment coefficient for 75° F (K_1) on figure 4–7a is 0.85 and that for a fine suspended-load concentration of 20,000 ppm (K_2) is 1.55. According to figure 4–7b, the effect of sediment size is only 40 percent as great for a diameter of 0.60 mm as it is for a diameter of 0.20 or 0.30 mm. Therefore, 40 percent of $(1.55-1.00) = 0.22$. The value

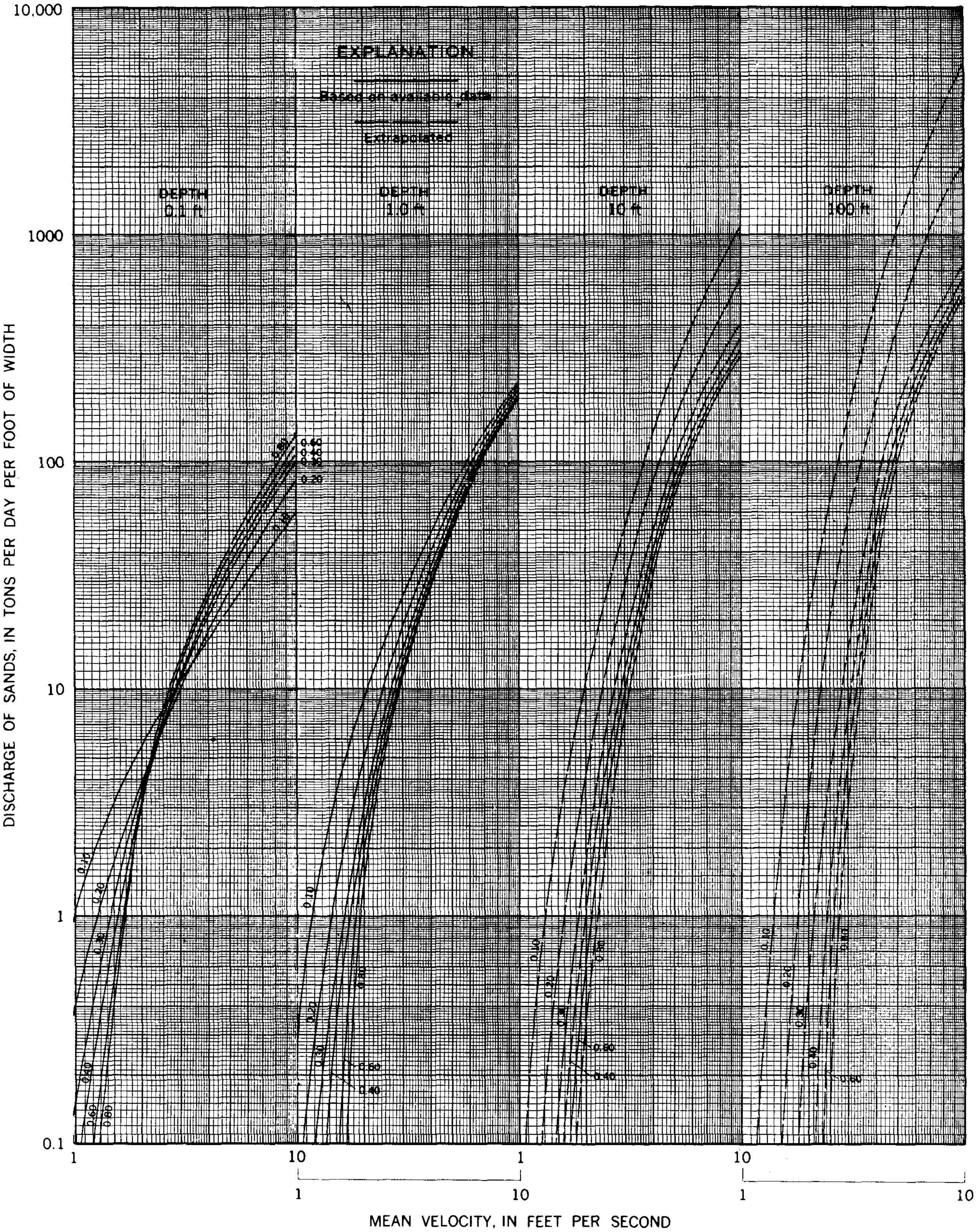


Figure 4–6.—Relationship of discharge of sands to mean velocity for six median sizes of bed sand, four depths of flow, and a water temperature of 60° F. From Colby (1964) and American Society of Civil Engineers (1975, p. 204).

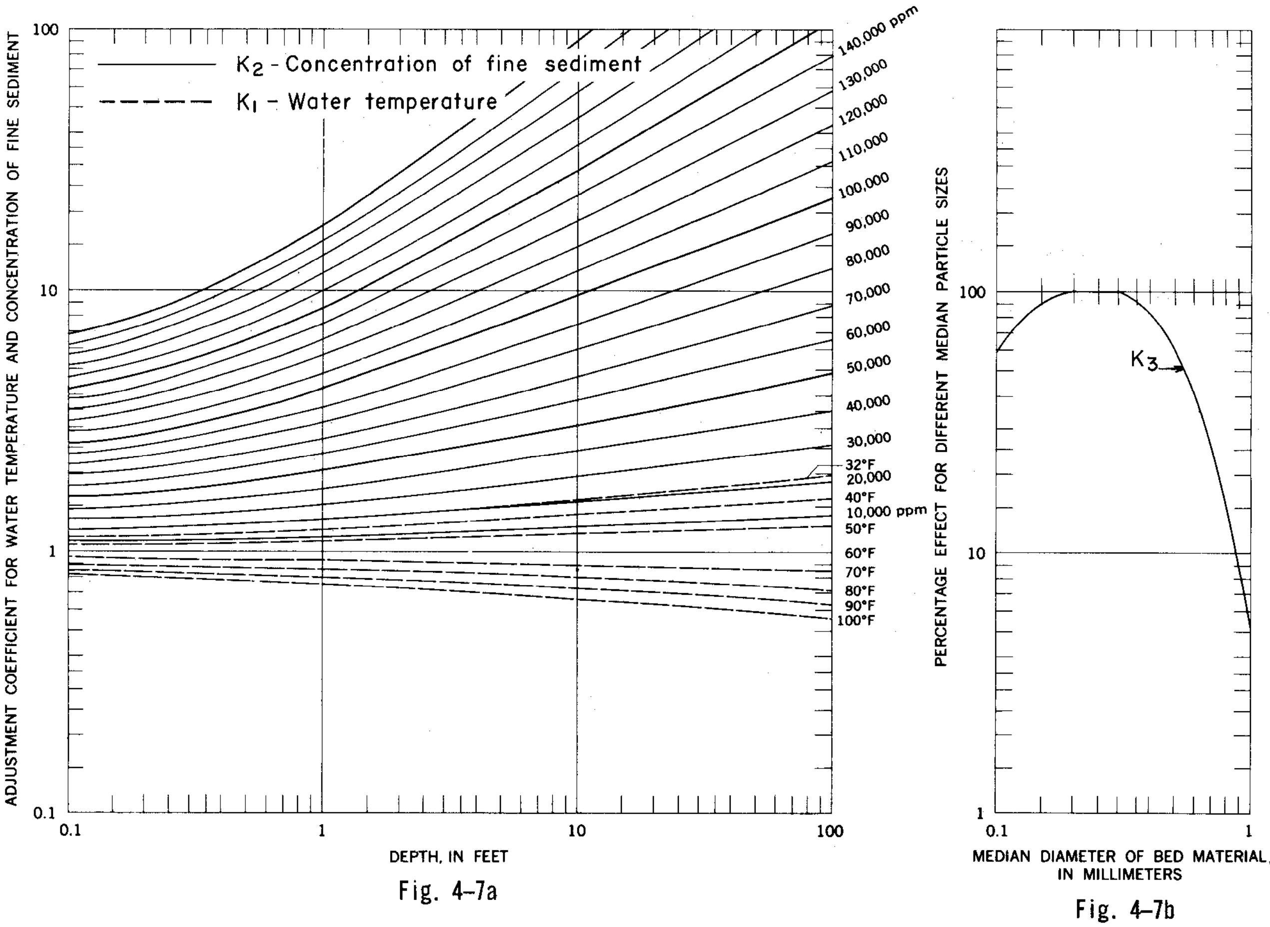


Figure 4-7.—Approximate correction factors for the effect of water temperature and concentration of fine sediment (4-7a) and sediment size (4-7b) on the relationship of discharge of sands to mean velocity. From Colby (1964) and American Society of Civil Engineers (1975, p. 205).

0.22 is then added to 1.00 to obtain the estimated adjustment coefficient for a diameter of 0.60 mm. The 105 tons/(day·ft) multiplied by 0.85 and by 1.22 gives 109 tons per day per foot of width.

Application and Limitations of Formulas

The lack of certainty in solving specific sediment-transport problems is in part a result of the extremely limited number of situations in which predictive techniques, such as bedload or bed-material transport formulas, have been substantiated by field measurement. Even for techniques that have been substantiated, little information is available about the specific hydraulic characteristics for comparison with conditions for the problem to be solved (Cooper et al. 1972).

Figure 4–8 illustrates a few of the major factors that can be considered in the application and limitations of sediment transport formulas. The availability of bed material ranges from no sand (box A), to an unlimited supply of sand in sizes less than 1 mm (box C), to bed material of gravel and boulders (box E). Flow characteristics range from highly unsteady or rapidly changing to steady and slowly changing.

Of the possible conditions illustrated by this diagram, the condition in box 2C most nearly fits the flow and sediment conditions used in developing transport formulas. Box 1C pertains specifically to the smaller streams with which SCS is concerned, not to rivers in which deep steady flows may transport gravel as they do sand. Through limited reaches and during high flows, shallow streams may also transport gravel and boulders. Frequently there is a transition from scour to deposition over a relatively short reach. Boxes adjacent to 2C (1C, 2B, 2D) can be considered a "gray" area for which correct solutions to sediment transport problems can be obtained by including the appropriate modifiers, such as changes in slope to match variations in discharge.

The effect of rapidly changing flow (top line on the chart) on bedload transport was the subject of a flume study by DeVries (1965). The mean grain size was 2.5 mm. After an equilibrium rate of transport was attained, the tailwater was suddenly lowered while the other factors were kept constant. DeVries computed the lowering of the bed level from scour and the change in rate of sediment transport during the transition to a new state of equilibrium by using several procedures, including the Meyer-Peter and Muller formula. He concluded that establishment and damping of a steady state are slow and that steady-state formulas are unreliable for predicting local, temporary transport for an unsteady state.

A subsequent flume study was made of the effect of introducing a substantial increase (65 percent) in bed-material load into a run where equilibrium flow and transport had been established (Rathbun and Guy 1967). The median size of the sand used was about 0.30 mm. This increase in load increased slope, decreased depth, and increased the transport rate. In another run, the rate of sediment input was reduced to about 50 percent of the equilibrium rate. At first the transport rate was about the same as during equilibrium flow; then, with the degradation of the upper end of the sand bed and the decrease in slope, the transport rate also decreased.

Flow characteristics	No sand → A	B	Unlimited supply of sand → C	D	Coarse gravel or boulders E
1. Highly unsteady or rapidly changing	1A	1B	1C	1D	1E
2. Steady or slowly changing	2A	2B	2C	2D	2E

Figure 4–8.—Characteristics of bed material.

Aggradation occurs in some channels even though hydraulic computations indicate that sediment should not deposit. It is not always known whether the aggradation occurred in the rising or falling stage of the hydrograph. Some of the unpredicted changes can be explained by variable bed roughness not accounted for in conventional hydraulic computations. Variable bed roughness does not necessarily explain all the inaccuracies in predicting the effects of hydraulic change on sediment transport, however, because some procedures do take into account the changes in bed roughness with various flows. Part of the problem may be due to unsteady flow, since steady-flow procedures fail to account for differences between stage and discharge.

In using computational procedures, it is very important that the supply of bed material just satisfies the capacity for transport under existing hydraulic conditions; that is, there can be neither a deficiency, resulting in scour, nor an excess, resulting in aggradation. A sand bed satisfies the necessary requirements for using bedload or bed-material transport formulas and that of bed-material availability if the bed is sand from bank to bank throughout the reach.

In considering the availability of bed materials, Kellerhals (1966) made a distinction between channels with a sand bed and channels with a gravel bed. According to his studies, channels with a gravel bed cannot be expected to obey the same laws as channels with a sand bed. One distinction is that ripple and dune formation are less significant in channels with a gravel bed.

In terms of particle size, the scarcity of particles in the 2- to 4-mm size fraction, as described by Sundborg (1956), creates a sharp division between predominantly sand-bed streams and predominantly gravel-bed streams. This division has been substantiated by data on sizes of bed material in various parts of the United States.

The segregation of particles in a mixture of sizes, including gravel, and the depth of scour before the formation of armor were the subjects of flume studies by Harrison (1950). The purpose was to determine the most critical condition for segregation and for building an armor during degradation. Harrison used the Einstein bedload function to calculate the limiting grain diameter for equilibrium flow. He determined that a value of ψ (a dimensionless parameter of transport capability) above 27 indicates negligible transport of bed material.

Harrison (1950) found that the representative grain roughness, k_s (assumed to be d_{65} in his procedures), increases during segregation and armor formation. On the basis of data from field and laboratory studies, Kellerhals (1966) computed the k_s values after armor formation to be the d_{90} size.

On the basis of these considerations, the following treatment is suggested for sediment problems in streams as categorized in figure 4–8.

1A, 2A.—For cohesive soil, cemented gravel, and rock, initiation of movement is the important factor in channel scour or bank erosion. Critical tractive force is related to the d_{75} of bank materials. Undisturbed cohesive soil exhibits erosion resistance that may result from one or several characteristics such as structure, permeability, consolidation, cementation, or cohesion. The influence of each of these characteristics has not been identified. Their cumulative effect on erosion resistance, however, can be determined by shear strength tests on undisturbed soil that has been saturated to duplicate moisture conditions during channel flow (Flaxman 1963).

1B, 2B.—A bed only partially covered with sand and exposing different material (cohesive soil, rock, etc.) as the fixed channel boundary indicates a limited sand supply at this specific location. Sediment transport formulas applied to this condition usually yield computed rates that exceed the actual rate. Test the potential for bank erosion by tractive force theory if the bank is composed of noncohesive materials; otherwise, use the procedures for cohesive soils.

1C, 2C.—A sand-covered bed is the condition used in sediment transport formulas if the problem to be solved requires (a) estimating the volume of bed-material transport during a specific interval of time and at a specific level of discharge or (b) comparing the bed-material transport in a reach with that in another reach in which changes in slope, cross section, or discharge may influence the design of a channel. If flow is unsteady, replace the steady-state procedures with the proper unsteady flow relationships, as previously mentioned.

2D.—Techniques for predicting transport rates of sand-gravel mixtures allow estimates of the potential for scour or aggradation. The probable depth of scour can be estimated by determining whether the maximum tractive force for a given flow will exceed the critical for the coarsest 5 to 10 percent of bed material. If the maximum tractive force exceeds the critical for the d_{90} to d_{95}, the depth of scour cannot be predicted unless still coarser material underlies the bed surface material. The amount of scour necessary to develop armor formed of the coarsest fraction can be determined from either the depth of scour or the volume of material removed in reaching this depth.

1D, 1E, 2E.—For gravel and gravel-boulder mixtures, the technique used for determining depth of scour and volume of material produced by scour is similar to that for sand-gravel mixtures (2D). Do not use bedload formulas for this type of material unless confined flow, steepness of slope, and uniformity of cross section provide relatively uniform discharge per foot of width. The highly variable velocity and discharge per foot of width in many alluvial channels is particularly conducive to deposition alternating with scour of coarse bed material.

Conditions favoring bed-material transport at or near a constant and predictable rate do not include delivery in slurries or other forms that change the viscosity and natural sorting processes of flow. Alluvial fills of mountain or foothill canyons are typical of conditions favoring viscous flow. Heavy storm runoff after many years of fill accumulation may produce debris or mud flows whose volume can be predicted only by field measurement.

Figures 4–9 to 4–11 compare the measured transport rates of bed-material sediment and the predicted rates. The predicted rates were computed by a number of formulas, except that the total bed-material discharge for the Colorado River at Taylor's Ferry (fig. 4–11) was determined from suspended-sediment samples by using the modified Einstein method (U.S. Department of the Interior 1958).

The formula-derived transport rates of bed-material sediment in Mountain Creek (fig. 4–9) follow the general trend of measurements more closely than the comparable rates for the Niobrara and Colorado Rivers (figs. 4–10 and 4–11, respectively). The transport characteristics of Mountain Creek may be more like the flume conditions from which most formulas were derived than like the transport conditions for the two rivers.

In an analysis in *Sedimentation Engineering* (American Society for Civil Engineers 1975), measurements in figures 4–10 and 4–11 were compared with rates computed by several formulas. It was concluded that calculated curves with slopes almost the same as those fitting the data (measurements) are useful even if they do not give the correct values of sediment discharge. Further, although no formula used in figures 4–10 and 4–11 gives lines parallel to those fitting the data, the Colby procedure and the Einstein bedload function consistently gave better results in this regard than the others. It was pointed out that the Colby procedure was derived in part from the Niobrara River data and that the close correspondence between the measured rates and the computed rates could be expected for this reason. Although the analysis included several formulas not described in this handbook, it did not include the Engelund-Hansen procedure, which appears to have merit comparable to that of the Colby and Einstein methods. (The Meyer-Peter or Meyer-Peter and Muller bedload formulas may be applicable for gravel and gravel-boulder mixtures with the limitations for 1D, 1E, and 2E). It appears that appropriate formulas should be used only to relate transport capacity between one reach and another and do not yield dependable quantitative results.

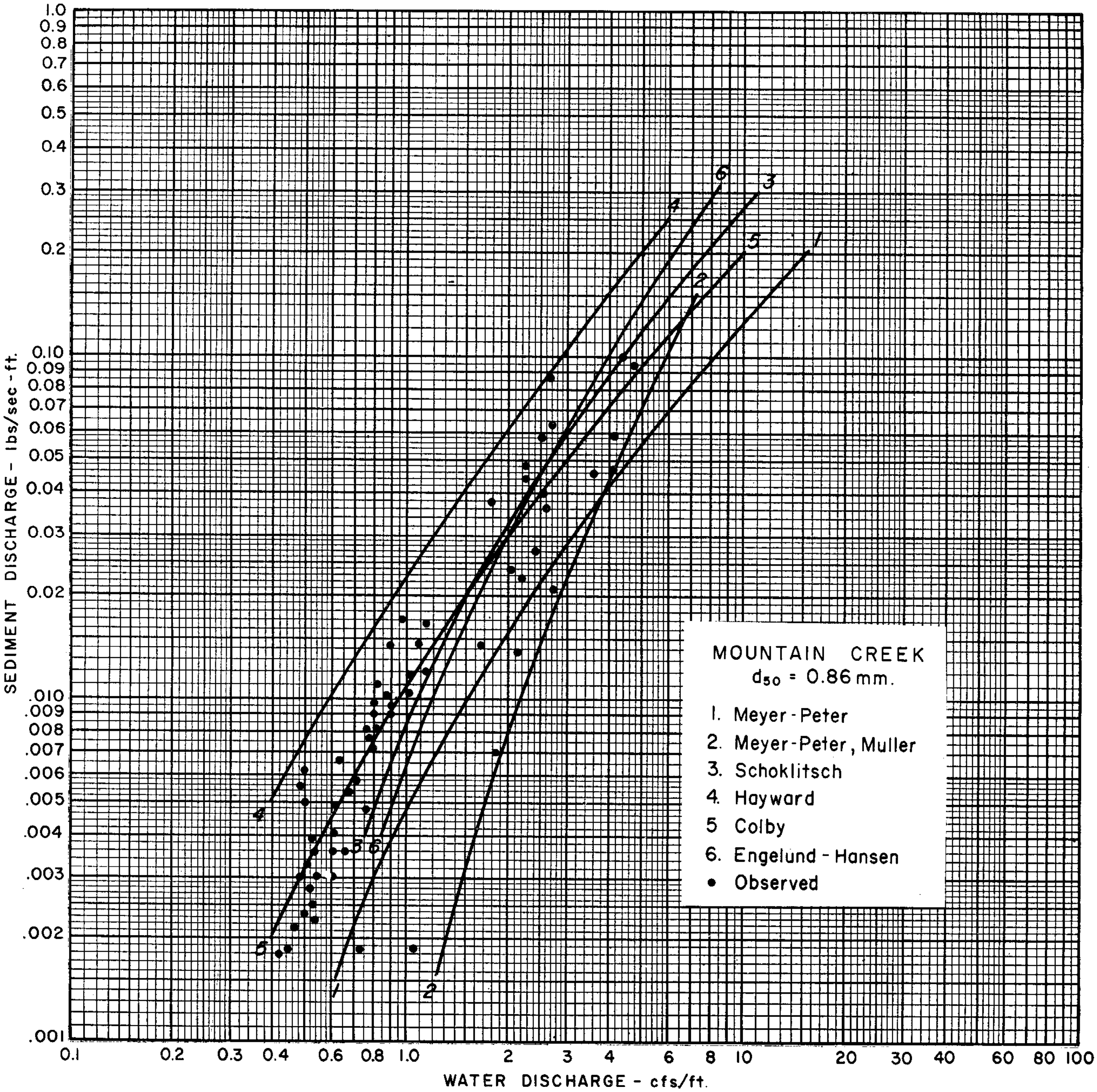


Figure 4-9.—Sediment rating curves for Mountain Creek near Greenville, S.C., according to several formulas compared with measurements. Adapted from Vanoni, Brooks, and Kennedy (1961, p. 7-8).

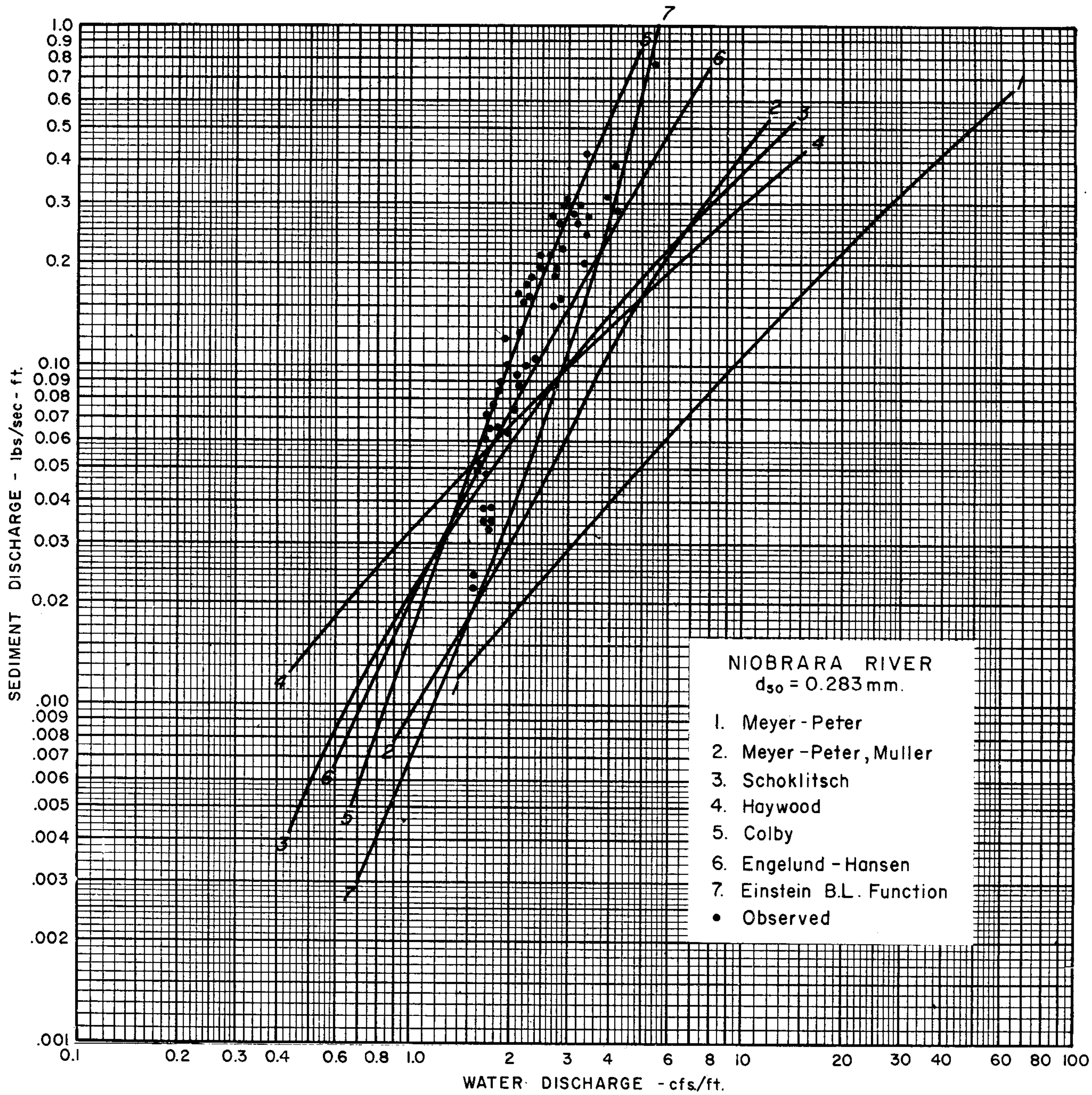


Figure 4–10.—Sediment rating curves for Niobrara River near Cody, Nebr., according to several formulas compared with measurements. Adapted from Vanoni, Brooks, and Kennedy (1961); American Society of Civil Engineers (1975, p. 221).

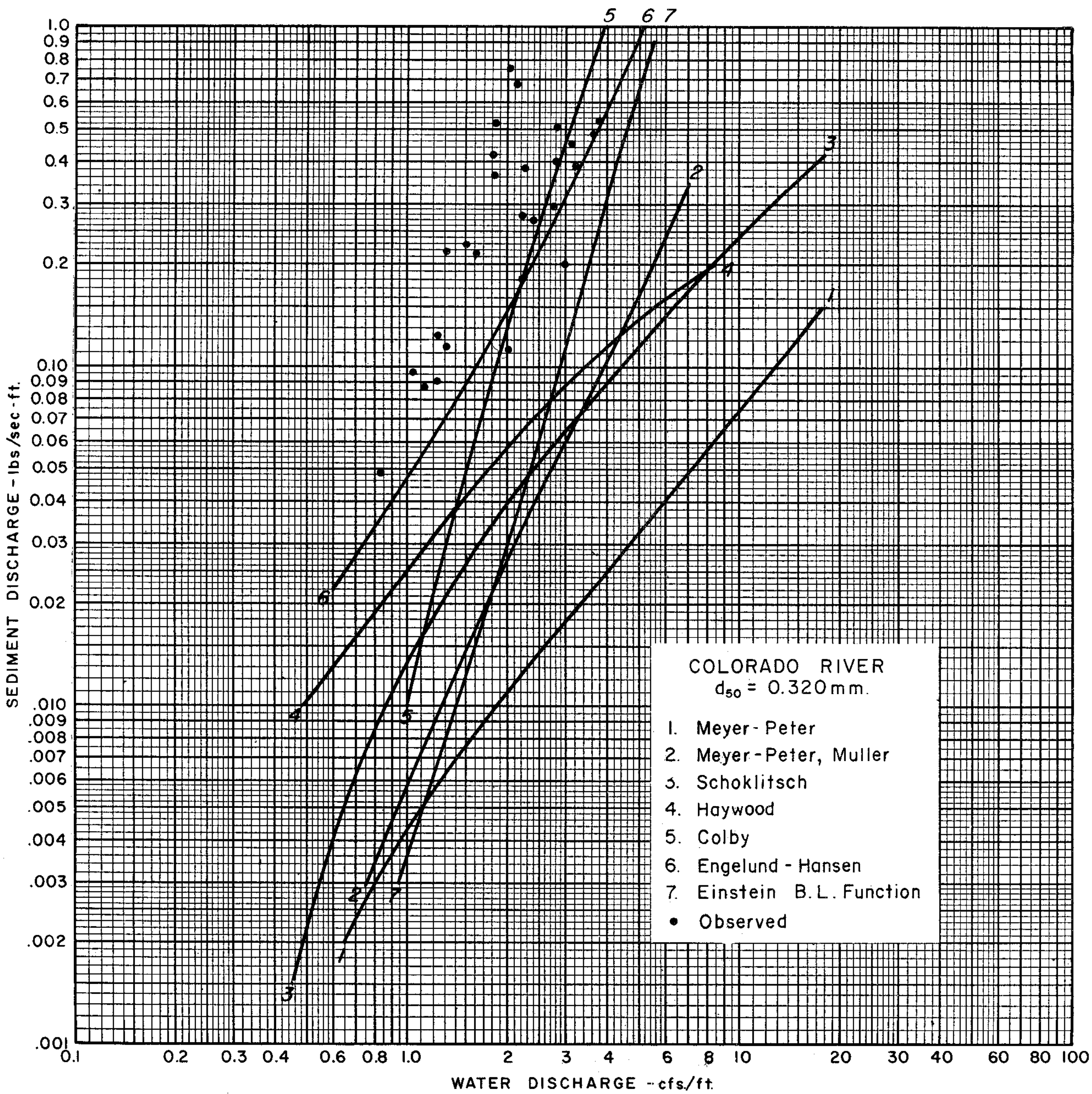


Figure 4–11.—Sediment rating curves for Colorado River at Taylor's Ferry, Ariz., according to several formulas compared with measurements. Adapted from Vanoni, Brooks, and Kennedy (1961); American Society of Civil Engineers (1975, p. 221).

The following example illustrates the similarities and differences in results obtained by applying two procedures to determine sediment transport capacity: the Schoklitsch formula and the Colby procedure.

An existing channel 20 ft wide having a bed slope of 0.002 ft/ft has inadequate capacity for controlling flooding of adjacent lands. It has been proposed that the width of this channel be increased to 30 ft to provide the necessary capacity. Field investigations show that an unlimited supply of sand is available for transport in the bed of the channel and that this sand has a d_{50} size of 0.30 mm. Water temperature is 60° F, and the concentration of fine sediment does not exceed 5,000 ppm.

For purposes of simplification, it is assumed that the banks have no effect on depth-discharge relationships. But the roughness of the banks and differences in roughness of the banks in both unimproved and improved reaches can in fact affect depth and velocity for a given discharge and thereby affect the rate of bed-material transport. The hydraulics of the flow, which includes distribution of shear on the banks as well as on the bed, must be determined by an established procedure before computing the bed-material transport.

The hydrograph used in this example is divided into segments to determine the discharge per foot of stream width as required for the computational procedures. The mean discharge and duration for each of the hydrograph segments are shown in table 4–1.

Table 4–1.—Discharge data for example channel problem, high flow

Hydrograph segment	Discharge per foot of width	
	20-ft channel	30-ft channel
	ft^3/s	ft^3/s
Rising stage:		
a. Mean flow for 2 hours, 90 ft³/s	4.5	3.0
b. Mean flow for 2 hours, 280 ft³/s	14.0	9.333
Falling stage:		
c. Mean flow for 3 hours, 240 ft³/s	12.0	8.0
d. Mean flow for 3 hours, 180 ft³/s	9.0	6.0
e. Mean flow for 3 hours, 40 ft³/s	2.0	1.333

The Schoklitsch formula requires data only for the amount of discharge per foot of width. The Colby procedure requires velocity and depth of flow. To determine velocity and depth for a given discharge (unless they are available from streamgage records), it is necessary either to assume an "n" roughness coefficient for use in the Manning equation or to obtain such values empirically. For solution of the example problem by the Colby procedure, two approaches are used. In one, a constant assumed "n" of 0.020 is used. In the other, the most recent and perhaps the most reliable procedure (Alam and Kennedy 1969) for predicting friction factors (and thereby depth, velocity, and discharge relationships) is used. See the appendix to this chapter for details of this procedure.

The data in table 4–2 indicate that in the stated problem the Schoklitsch formula predicts considerably less sediment transport than either of the Colby approaches. This difference may be due to the fact that the Schoklitsch formula predicts bedload and the Colby procedure accounts for suspended bed material as well as bedload. The difference between the two Colby predictions can be attributed to the different approaches for estimating the depth of flow. The first assumes n = 0.020 and a normal depth based on bed slope equal to friction slope; the second assumes a normal depth based mostly on grain roughness for friction slope.

The Alam and Kennedy friction factors are never in the lower flow regime for this set of calculations; therefore, bedform changes had little effect on the results. All three results indicate a slight, but negligible, reduction (less than 5 percent) in sediment transport capacity for the wider channel.

The next step in the analysis is to determine whether lower flows would give different results. For this computation, 20 percent of the discharges indicated in table 4–1 are used in table 4–3.

Table 4–4 shows the amount of sediment transported as computed by the two procedures. Table 4–4 again indicates considerable difference between the Schoklitsch and Colby predictions, but less than that shown in table 4–2. This smaller difference can be attributed to the smaller loads in suspension for the lower flows. All three predictions, however, indicate greatly reduced sediment transport capacity for the wider (30-ft) channel (9, 17, and 32 percent, respectively). The most significant reduction, almost one-third, is predicted by the Colby procedure using the Alam and Kennedy friction factors. It is believed that the Colby procedure

Table 4–2.—Sediment transport computed for various flows

Discharge segment	Schoklitsch formula		Colby procedure: Using n = 0.020		Colby procedure: Using Alam and Kennedy friction factors	
	20-ft width	30-ft width	20-ft width	30-ft width	20-ft width	30-ft width
	lb	*lb*	*lb*	*lb*	*lb*	*lb*
a	44,135	42,840	97,285	86,720	109,270	103,225
b	142,760	141,470	347,085	344,210	412,425	543,140
c	182,995	181,060	442,745	426,435	590,170	564,565
d	136,280	134,340	328,735	310,100	516,280	431,920
e	27,270	25,330	50,710	42,765	46,180	31,190
Total	533,440	525,040	1,226,560	1,210,230	1,674,325	1,674,040
Ratio $\left(\frac{\text{20-ft width}}{\text{30-ft width}}\right)$	$\frac{525,040}{533,440}$ = 98.43 percent		$\frac{1,210,230}{1,266,560}$ = 95.55 percent		$\frac{1,674,040}{1,674,325}$ = 99.98 percent	

Table 4–3.—Discharge data for example channel problem, lower flow

Hydrograph segment	Discharge per foot of width: 20-ft channel	Discharge per foot of width: 30-ft channel
	ft³/s	*ft³/s*
Rising stage:		
a. Mean flow for 2 hours, 18 ft³/s	0.9	0.6
b. Mean flow for 2 hours, 56 ft³/s	2.8	1.87
Falling stage:		
c. Mean flow for 3 hours, 48 ft³/s	2.4	1.6
d. Mean flow for 3 hours, 36 ft³/s	1.8	1.2
e. Mean flow for 3 hours, 8 ft³/s	0.4	0.267

using the Alam and Kennedy factors most closely reflects the influence of variable bed forms that are more pronounced during low to moderate flows.

This example clearly shows that estimates of the absolute rates of sediment transport vary according to the procedure. But the study also shows that the relative rates can be insensitive to choice of procedure if variation in bed forms is not a factor, as for channel performance at peak discharge. In many stability problems, however, the performance of the channel during one or more low to moderate flows must be considered. Formulas and procedures that determine the effect of variable bed forms on depth, velocity, and discharge relationships and, thereby, on bed-material discharge afford greater flexibility for all purposes.

Table 4–4.—Sediment transport computed for lower flows

Discharge segment	Schoklitsch formula		Colby procedure			
			Using n = 0.020		Using Alam and Kennedy friction factors	
	20-ft width	30-ft width	20-ft width	30-ft width	20-ft width	30-ft width
	lb	*lb*	*lb*	*lb*	*lb*	*lb*
a	6,760	5,470	9,970	7,195	450	700
b	26,485	25,195	53,280	46,705	61,225	41,645
c	33,500	31,560	67,580	54,615	66,255	46,245
d	24,155	22,220	43,710	36,000	39,245	24,500
e	2,355	415	3,315	2,525	940	415
Total	93,255	84,860	177,855	147,040	168,115	113,505
Ratio $\left(\frac{\text{30-ft width}}{\text{20-ft width}}\right)$	$\frac{84,860}{93,255}$ = 91.00 percent		$\frac{147,040}{177,855}$ = 82.67 percent		$\frac{113,505}{168,115}$ = 67.52 percent	

Summary of Procedures for Evaluating Bed-Material Transport Problems

Problems of bed-material transport require consideration of three elements: (1) existing conditions, (2) availability of bed material, and (3) natural or artificial changes in stream or watershed conditions. The existing conditions can be best determined by field investigation and analysis. Surveys of old and new cross sections, use of techniques for identifying depth of scour or aggradation, and comparison of aerial photographs all facilitate definition of the problems.

Although the correct identification and analysis of existing bed-material transport conditions are important, most problems require projections of what will or can occur rather than what is now occurring. The availability of bed material and the impact of change are the key elements of such projections.

Equilibrium can be achieved only if bed material is being introduced into the reach at a rate comparable to that at which bed material moves out of the reach. Problems arise when the amount introduced is greater or less than the transport capacity of the flow. In other words, equilibrium transport seldom causes problems but a change from equilibrium to nonequilibrium transport often does.

The supply of bed material can exceed transport capacity during unusually high discharges. This excess can be caused by development of new and substantial sources of bed material within or adjacent to the problem reach or by channel changes that may increase transport capacity in the upstream reach but not in the downstream reach. Determing the availability of bed material is largely a field problem. To be readily available to channel flow, sediment must be in the stream system. The coarse particles in an upland soil tend to lag behind during erosion. Gullies that feed directly into the stream system and that expose soils with a large proportion of particles of bed-material size can be major contributors but do not in themselves constitute an immediate and unlimited stream channel supply.

Streambanks that have, at least in part, soil textures comparable to those in the bed, can be a ready source of supply, depending on the ease with which the flow can erode the material. A frequently used emergency flood-protection measure is to bulldoze streambed materials to each side to form banks or levees. These banks are a ready source of supply. Their erosion and the consequent deterioration of channel alignment result in overloading the flow and downstream aggradation.

Scour of bed material can result from an undersupply of sediment in an alluvial reach. Upstream changes in watershed or stream conditions that can reduce the supply of incoming bed material include the removal of supply by major flood scour and the construction of reservoirs, debris basins, or other structures.

In addition to cutting off the supply of bed material to the reach downstream, a reservoir can materially influence the stability of the channel bed and banks by modifying the flow. For example, a detention structure that controls a high flood peak can thereby extend the duration of released flows by days. The resulting bed and bank scour may be extensive because of the energetic discharge of clear water.

Table 4–5 is a checklist of procedures to consider in solving problems of bed-material transport. The last column in this table indicates that a field evaluation is important to the solution of any such problem. Because of the variety of factors that can influence their solution, most problems are not routine and solving them requires the assistance of well-trained and experienced personnel. The first step should always be a field evaluation of existing or potential problems related to sediment transport. With experience, well-trained personnel frequently can find answers to questions of stability, degradation, or aggradation by relating the availability of bed material to proposed changes in the hydraulics of the flow without resorting to formulas. If formulas must be used, it should be recognized that the results are qualitative and not quantitative. Observations of similar streams having comparable drainage areas, geology, soils, topography, and runoff often provide guidance on the probable stability.

Table 4–5.—Checklist of procedures for solving bed-material transport problems

Item	Analysis procedure: Tractive stress[1]	Comparative hydraulics[2]	Bed material formulas	Field evaluation
Problem characteristics:				
Erodibility of bed	x			x
Erodibility of bed and banks	x			x
Erodibility of banks	x			x
Channel aggradation		x	x	
Volume of bed material			x	x
Effects of channel change		x	x	x
Channel boundary characteristics:				
Cohesive soils	x			x
Cohesive soils or rock with intermittent deposits of sand or gravel	x			x
Sand $\leq$1.0 mm	x	x	x	x
Sand $\leq$1.0 mm with <10% gravel	x	x	x	x
Gravel, gravel mixed with sand	x		[3]	x
Gravel and boulders	x		[3]	x
Hydraulic characteristics:				
In problem reach:				
Steady state or slowly changing	x	x	x	x
Rapidly changing	x	x		x
Cross section—slope upstream vs problem reach:				
About the same	x	x	x	x
Steeper slope	x	x	x	x
Wider channel	x	x	x	x
Narrower channel	x	x	x	x

[1]For cohesive soil boundaries, analysis may include tractive power (tractive stress times mean velocity).
[2]Comparison of relationships between depth, velocity, and unit discharge in two or more reaches.
[3]Special situations, see page 4–19.

Suspended-sediment load includes both the bed-material load in suspension and the wash load, as shown in figure 4–2. If erosion of fine-texured soils is the chief source of sediment, the wash load, not the bed-material load, usually constitutes the bulk of the sediment discharge. No method exists for predicting rates of wash-load transport unless there is a substantial amount of data on concentrations of suspended sediment during measured discharges.

Suspension Mechanism

Bagnold (1966) explains the suspension mechanism as follows:

> Isotropic turbulence cannot by definition be capable of exerting any upward directed stress that could support a suspended load against gravity. For any suspended solid must experience over a period of time a downward flux of eddy momentum equal on the average to the upward flux. A swarm of solids would be dispersed equally in all directions by diffusion along uniform concentration gradients, but the center of gravity of the swarm would continue to fall toward a distant gravity boundary.
>
> The center of gravity of a swarm of solids suspended by shear turbulence, on the other hand, does not fall toward the gravity shear boundary. The excess weight of the solids remains in vertical equilibrium. It follows therefore that the anisotropy of shear turbulence must involve as a second-order effect a small internal dynamic stress directed perpendicularly away from the shear boundary. In other words, the flux of turbulent fluid momentum away from the boundary must exceed that toward it. . . . The turbulence appears to be initiated and controlled by a process akin to the generation of surface waves by a strong wind. An upwelling on the part of a minor mass of less turbulent boundary fluid intrudes into an upper, faster moving layer, where its crest is progressively torn off, like spray, and mingles with the upper layer. Corresponding motion in the reverse sense are [sic] absent or inappreciable.
>
> Since there cannot be a net normal transport of fluid, the return flow must be effected by a general sinking toward the boundary on the part of a major mass of surrounding fluid.

The settling rate for sediment particles of uniform density increases with size, but not proportionally. The settling rate for particles smaller than about 0.062 mm varies approximately as the square of the particle diameter, whereas particles of coarse sand settle at a rate that varies approximately as the square root of the diameter. The settling rate for particles of intermediate size varies at an intermediate rate. The dividing line between sediments classed as silts and those classed as sands is the 0.062-mm size. Clay and silt particles usually are distributed fairly uniformly in a stream, but sand particles usually are more concentrated near the bottom. The degree of variation is a function of the coarseness of the particle (fig. 4–12).

The lateral distribution of suspended sediment across a stream is fairly uniform in both deep and shallow flows except below the junction of a tributary carrying material at a concentration substantially different from that of the main stream. The flow from the tributary tends to remain on the entrance side of the channel for some distance downstream.

Sampling and Laboratory Procedures

The U.S. Geological Survey collects most of the suspended-sediment samples in this country. Samples are collected by lowering and raising an integrating sampler vertically in the flow at a uniform rate. Travel time to and from the streambed is regulated so that the container is not quite full of the water-sediment mixture when it returns to the surface. This regulation provides uniform sampling for the sampled depth of flow. Flows are sampled to within about 4 in. of the bed.

Point-integrating samplers have a tripping mechanism that enables sampling at any point in the flow. Data on concentration and composition of the bed material are used in computing the total bed-material load. Point-integrating samplers are sometimes used in streams too deep for equipment that can collect integrated samples only. Sixteen feet is about the maximum depth for obtaining integrated samples.

Laboratory procedures used in handling the samples include weighing the container holding the water-sediment mixture and then decanting the clear liquid, evaporating the remaining moisture, and weighing the dry sediment. The ratio of the dry weight of the sediment times 10^6 to the weight of the water-sediment mixture is the sediment concentration in parts per million. The suspended-sediment concentration can be experssed in milligrams per liter by using the following formula (American Society of Civil Engineers 1975, p. 403).

$$\text{Concentration in milligrams per liter} = A\left(\frac{\text{weight of sediment x } 10^6}{\text{weight of water-sediment mixture}}\right) \quad \textbf{4–6}$$

Factor A is given in table 4–6.

Suspended-sediment load stations can be classified according to how often they collect and report data. Stations reporting daily can collect several samples during a high or variable discharge. Periodic stations collect samples about every 2 weeks or less frequently. Daily stations report mean discharge, sediment concentration in tons, and a summation of the latter for the month and year. Periodic stations usually report data for only the day of sampling. Size distribution is frequently obtained for representative samples.

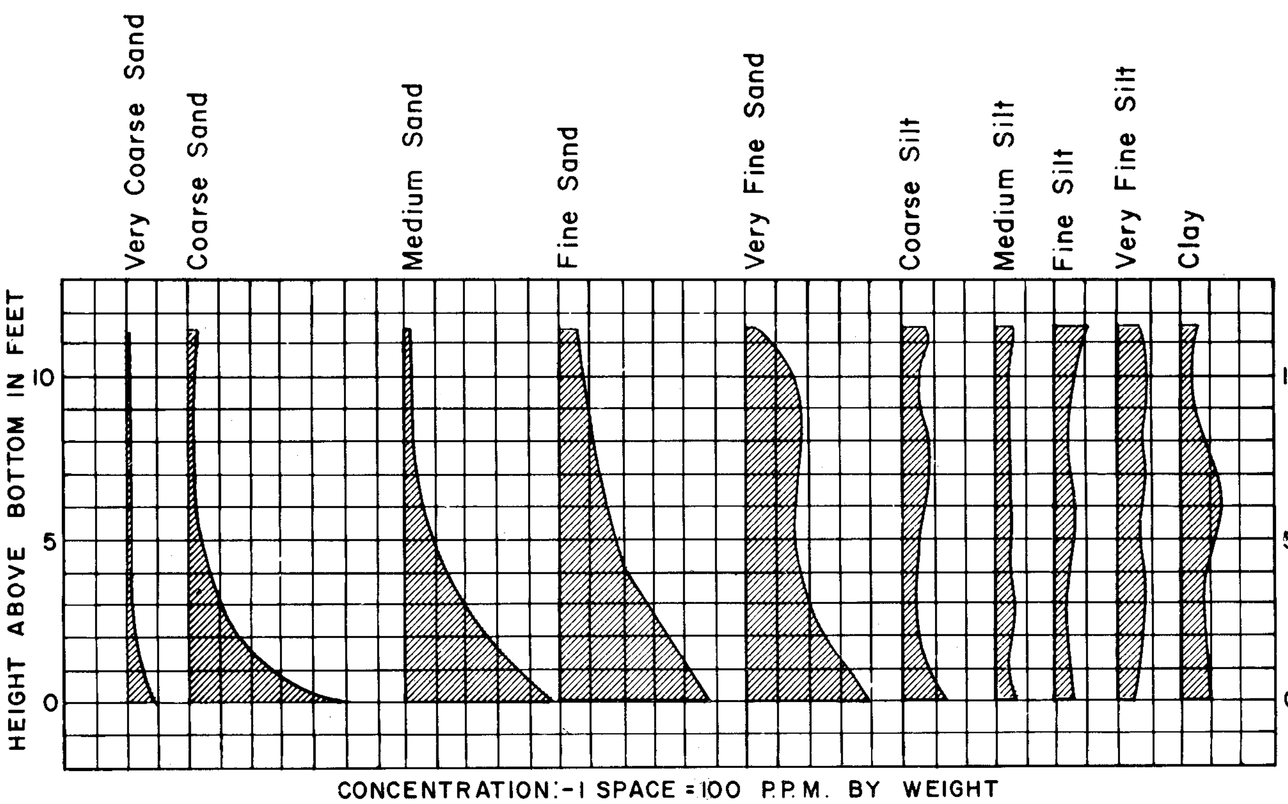


Figure 4–12.—Vertical distribution of sediment in Missouri River at Kansas City, Mo. From Federal Inter-Agency River Basin Committee (1963, p. 28).

Table 4-6.—Factor A for computing sediment in milligrams per liter by equation 4-6

Wt of sediment / Wt of sediment-water mixture × 10^6	A	Wt of sediment / Wt of sediment-water mixture × 10^6	A
0 - 15,900	1.00	322,000 - 341,000	1.26
16,000 - 46,900	1.02	342,000 - 361,000	1.28
47,000 - 76,900	1.04	362,000 - 380,000	1.30
77,000 - 105,000	1.06	381,000 - 398,000	1.32
106,000 - 132,000	1.08	399,000 - 416,000	1.34
133,000 - 159,000	1.10	417,000 - 434,000	1.36
160,000 - 184,000	1.12	435,000 - 451,000	1.38
185,000 - 209,000	1.14	452,000 - 467,000	1.40
210,000 - 233,000	1.16	468,000 - 483,000	1.42
234,000 - 256,000	1.18	484,000 - 498,000	1.44
257,000 - 279,000	1.20	499,000 - 513,000	1.46
280,000 - 300,000	1.22	514,000 - 528,000	1.48
301,000 - 321,000	1.24	529,000 - 542,000	1.50

If daily or more frequent data on the concentration of suspended sediment are available, tons per day can be computed by plotting the concentration directly on a chart showing gage height against time. Draw a smooth curve through the plotted points and read the daily mean concentration from the graph. If data on rapidly changing concentration and water discharge are available, divide the graphs into smaller increments of time (American Society of Civil Engineers 1975, p. 345).

Sediment-Rating Curve and Flow-Duration Curve Method of Computing Suspended-Sediment Load

Periodic data on suspended sediment or short-term daily data are sometimes extended for use as average annual yeilds by constructing sediment-transport rate and flow-duration curves. A sediment-transport rate curve constructed by plotting discharge and sediment-load data in tons is shown in figure 4–13. It is not essential to plot all the data available, but plot enough over a wide range of discharges to be able to draw a curve that will cover and perhaps extend the range of data.

To construct a flow-duration curve, divide data on mean discharges into a series of classes over a range that has been recorded at this station. Then, count the number of days within each class. Determine the percentage of time in each class and plot the midpoint on log-probability paper against the accumulated percentage at that point. Figure 4–14 is an example of a flow-duration curve. Table 4–7 illustrates how to use the sediment-transport rate curve and the flow-duration curve to determine the annual sediment yield for the period on which the flow-duration curve is based. Construction of this particular curve is based on the total number of days of record. Each segment of the curve represents the proportion of a composite day in which a particular flow occurs during the period of record. For example, in figure 4–14 discharge is 100 ft³/s or greater for 10 percent of a composite day. Methods of preparing flow-duration curves are described in detail by Searcy (1959).

The figures in column 1, table 4–7, refer to segments of the flow-duration curve; for example, the entries in horizontal line 1 are for the segment between 0.01 percent and 0.05 percent of the composite day.

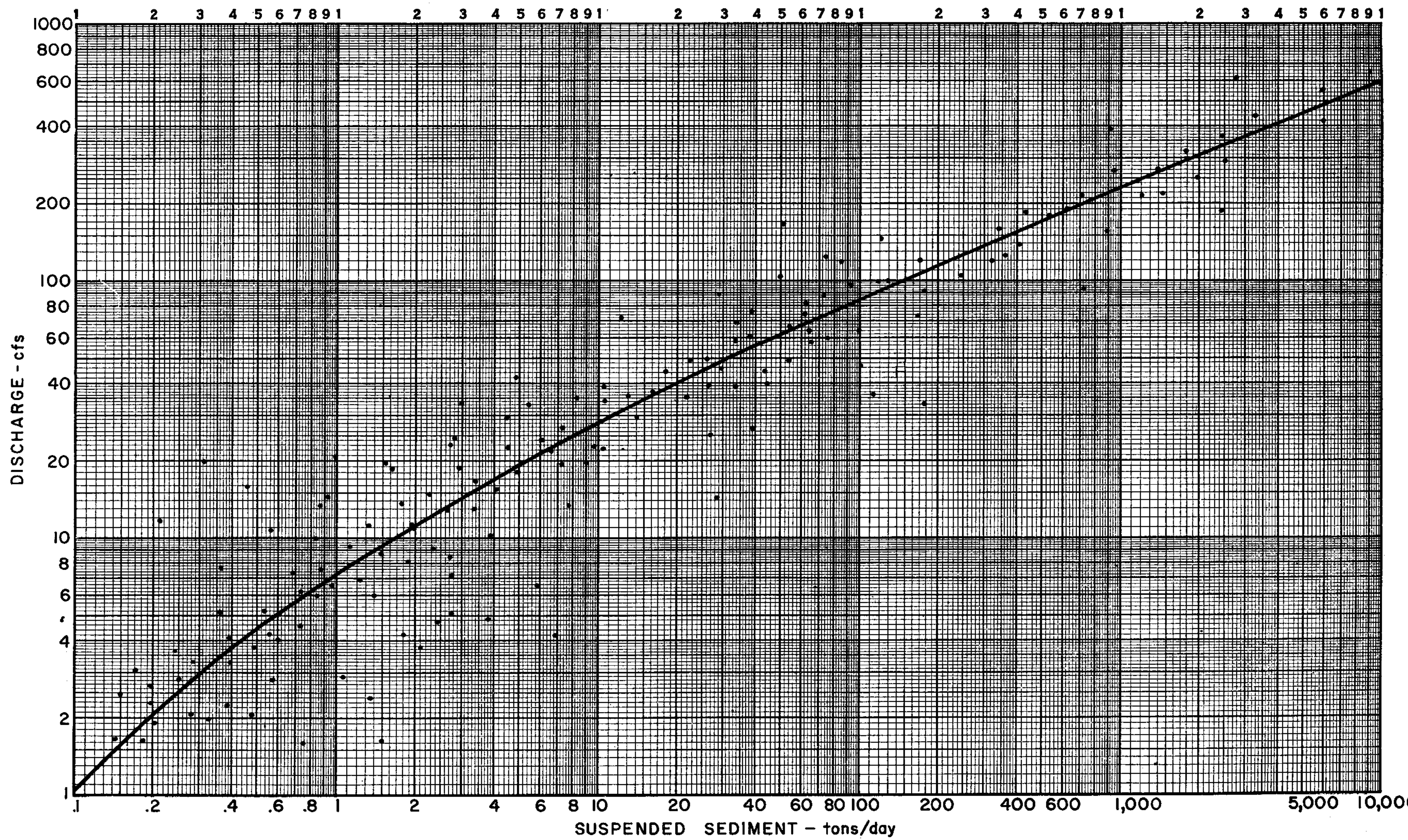


Figure 4-13.—Sediment rating curve, Cottonwood Creek, any State.

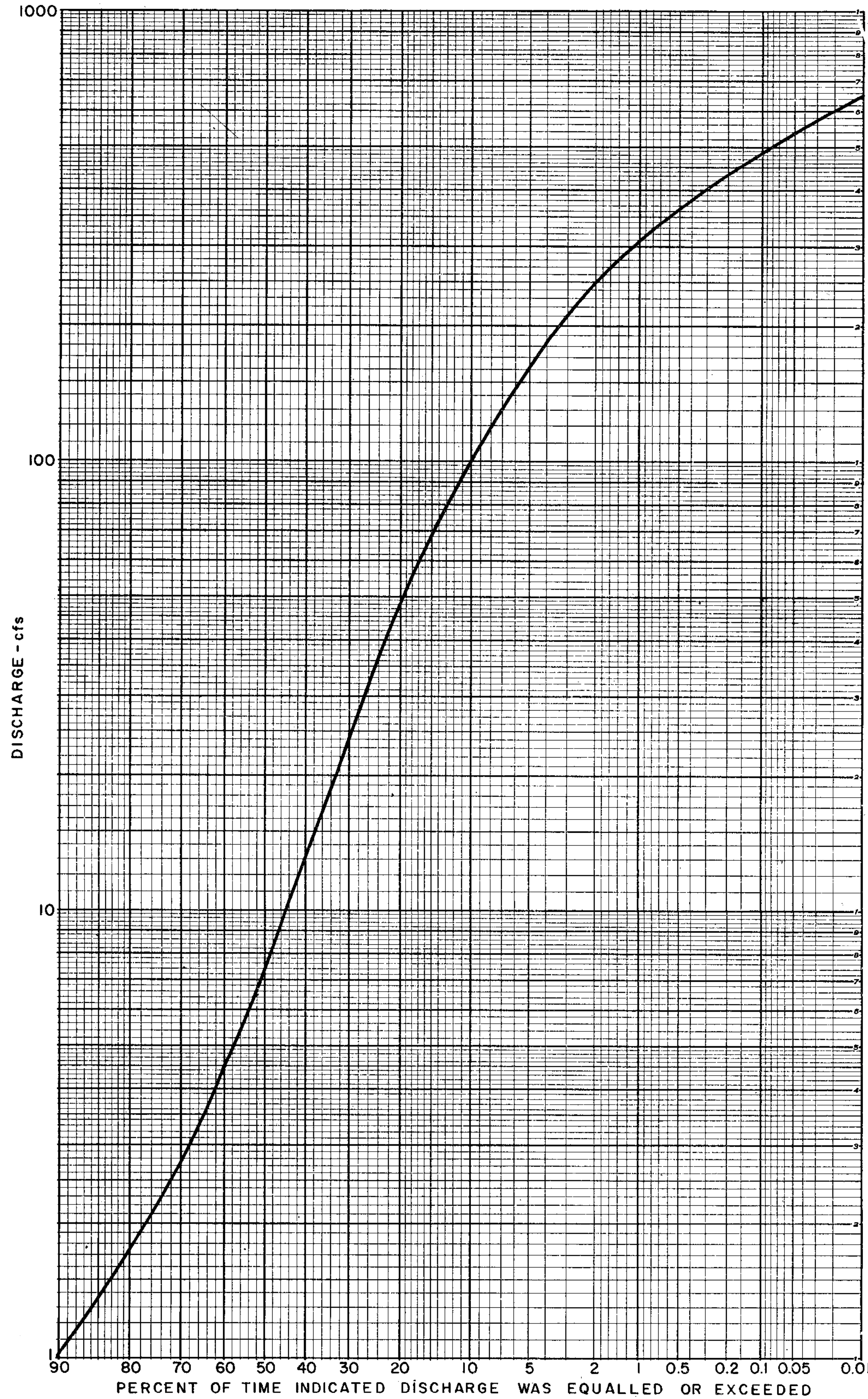


Figure 4–14.—Flow-duration curve, Cottonwood Creek, any State.

Table 4–7.—Computation of average annual suspended-sediment load, Cottonwood Creek, Any State

1 Percentage limits	2 Percentage interval	3 Percentage (mid ordinate)	4 Discharge Q_w	5 Sediment load, Q_s	6 Discharge (Q_w) per day Col. 2 x Col. 4	7 Sediment load (Q_s) per day Col. 2 x Col. 5
			ft³/s	*tons*	*ft³/s*	*tons*
0.01 - 0.05	0.04	0.030	590	9,000	0.24	3.6
0.05 - 0.1	0.05	0.075	505	6,400	0.25	3.2
0.1 - 0.5	0.4	0.30	400	3,500	1.6	14.0
0.5 - 1.5	1.0	1.0	310	1,900	3.1	19.0
1.5 - 5	3.5	3.25	200	700	7.0	24.5
5 - 15	10	10	100	145	10.0	14.5
15 - 25	10	20	47	28	4.7	2.8
25 - 35	10	30	25	8	2.5	0.8
35 - 45	10	40	13	3	1.3	0.3
45 - 55	10	50	7	1	0.7	0.1
55 - 65	10	60	4	0.5	0.4	0.05
65 - 75	10	70	3	—	0.3	—
75 - 85	10	80	2	—	0.2	—
85 - 95	10	90	1	—	0.1	—
				Total	32.39	82.8

Annual sediment load = 82.8 x 365.25 = 30,240 tons

References

Alam, A.M., and J.F. Kennedy. 1969. Friction factors for flow in sand-bed channels. Proc. Am. Soc. Civ. Eng., J. Hydraul. Div. 95 (HY6): 1,973–1,992

American Society of Civil Engineers. 1975. Sedimentation engineering. Man. Rep. Eng. Pract. 54, ASCE, 745 p.

Bagnold, R.A. 1966. An approach to the sediment transport problem from general physics. U.S. Geol. Surv. Prof. Pap. 422–I.

Colby, B.R. 1964. Discharge of sands and mean velocity relationships in sand-bed streams. U.S. Geol. Surv. Prof. Pap. 462–A, 47 p.

Colby, B.R., and C.H. Hembree. 1955. Computations of total sediment discharge, Niobrara River near Cody, Nebraska. U.S. Geo. Surv. Water Supply Pap. 1357, 187 p.

Colby, B.R., and C.H. Scott. 1965. Effects of water temperature on the discharge of bed material. U.S. Geol. Surv. Prof. Pap. 462–G, 25 p.

Cooper, R.H. and A.W. Peterson. 1970. Discussion of "Coordination in Mobile-Bed Hydraulics." Proc. Am. Soc. Civ. Eng., J. Hydraul. Div. 96 (HY9):1,880–1,886.

Cooper, R.H., A.W. Peterson, and T. Blench. 1972. Critical review of sediment transport experiments. Proc. Am. Soc. Civ. Eng., J. Hydraul. Div. 98 (HY5):827–843.

DeVries, M. 1965. Considerations about nonsteady bedload transport in open channels. Delft Hydraul. Lab., Pub. 36, Sept. 1963, 11 p.

Einstein, H.A. 1944. Bed-load transportation in Mountain Creek. Soil Conserv. Serv. Tech. Pap. 55, 54p.

Einstein, H.A. 1950. The bed-load function for sediment transportation in open channel flows. U.S. Dep. Agric. Tech. Bull. 1026, 71 p.

Einstein, Hans A., and Nicholas L. Barbarossa. 1952. River channel roughness. Trans. Am. Soc. Civ. Eng. 117 (paper no. 2528):1,121–1,132.

Engelund, Frank, and Eggert Hansen. 1967. A monograph on sediment transport in alluvial streams. Teknisk Forlag, Copenhagen, Denmark, 62 p.

Federal Inter-Agency River Basin Committee, Subcomm. on Sedimentation. 1963. A study of methods used in measurement and analysis of sediment load of streams. Rep. No. 14, 151 p.

Flaxman, E.M. 1963. Channel stability in undisturbed cohesive soils. Am. Soc. Civ. Eng., J. Hydraul. Div. 89(HY2):87–96.

Fortier, Samuel, and Fred C. Scobey. 1926. Permissible canal velocities. Am. Soc. Civ. Eng. Trans. 89(paper no. 1588):940–984.

Gilbert, G. K. 1914. The transportation of debris by running water. U.S. Geol. Surv. Prof. Pap. 86, 259 p.

Guy, H. P., D. B. Simons, and E. V. Richardson. 1966. Summary of alluvial channel data from flume experiments, 1956–61. U.S. Geol. Surv. Prof. Pap. 462–I, p. 1–96.

Harrison, A.S. 1950. Report on special investigation of bed sediment segregation in a degrading bed. Univ. Calif. Inst. Eng. Res., Berkeley. Ser. 33, No. 1, 205 p.

Haywood, O. G., Jr. 1940. Flume experiments on the transportation by water of sands and lightweight materials. Unpub. thesis for D.Sc., Mass. Inst. Tech., 122 p.

Kellerhals, R. 1966. Stable channels with gravel paved beds. Am. Soc. Civ. Eng. Water Resour. Eng. Conf., Denver, Colo. Prepr. 330, 38 p.

Lane, E. W. 1955. Design of stable channels. Am. Soc. Civ. Eng. Trans. 120(paper no. 2776):1,234–1,279.

Lovera, F., and J. F. Kennedy. 1969. Friction-factors for flat-bed flows in sand cannels. Proc. Am. Soc. Civ. Eng., J. Hydraul. Div. 95(HY4): 1,227–1,234.

Meyer-Peter, E., and R. Muller. 1948. Formulas for bed load transport. Int. Assoc. Hydraul. Res., 2nd Meeting, Stockholm. p. 39–64.

Rathbun, R. E., and H. P. Guy 1967. Effect of non-equilibrium flow conditions on sediment transport and bed roughness in a laboratory alluvial channel. Proc. 12th Congr. Int. Assoc. Hydraul. Res. 1:187–193.

Searcy, J. K. 1959. Flow-duration curves. U.S. Geol. Surv. Water Supply Pap. 1542–A, p. 1–33.

Sheppard, J. R. 1960. Investigation of Meyer-Peter, Muller bedload formulas. Sedimentation Section, Bureau of Reclamation, U.S. Department of the Interior, 22 p.

Shields, A. 1936. Application of similarity principles and turbulence research to bed-load movement. Trans. by W. P. Ott and J. C. Van Uchelen, Soil Conserv. Serv. Coop. Lab., Calif. Inst. Tech., Pasadena, Calif.

Shulits, S. 1935. The Schoklitsch bed-load formula. Engineering 139: 644–646, 687.
Shulits, S., and R. D. Hill, Jr. 1968. Bedload formulas, Part A. Penn. State Univ., Coll. Eng., 153 p.
Simons, D. B., E. V. Richardson, and W. L. Hauschild. 1963. Some effects of the fine sediment on flow phenomena. U.S. Geol. Surv. Water Supply Pap. 1498–G, 47 p.
Sundborg, Ake. 1956. The River Klaralven, a study of fluvial processes. Bull. 52, Inst. Hydraul., Royal Inst. Tech., Stockholm, 315 p.
Sutherland, A. J. 1967. Proposed mechanism for sediment entrainment by turbulent flows. J. Geophys. Res. 72(24):6,183–6,194.
U.S. Department of Transportation, Federal Highway Administration. 1975. Highways in the river environment, hydraulic and environmental design considerations. Training and Design Manual, 410 p.
U.S. Department of the Army, Corps of Engineers, Missouri River District. 1968. Missouri River, channel regime studies. Sediment Ser. 13A, 13 p.
U.S. Department of the Interior, Bureau of Reclamation, Sediment Section. 1958. Interim report, total sediment transport program, Lower Colorado River basin. 175 p.
Vanoni, V. A., and N. H. Brooks. 1957. Laboratory studies of the roughness and suspended load of alluvial streams. Calif. Inst. Tech. Sediment. Lab. Rep. No. E–68, 121 p.
Vanoni, V. A., N. H. Brooks, and J. F. Kennedy. 1961. Lecture notes on sediment transportation and channel stability. Calif. Inst. Tech. W. M. Keck Lab. Hydraul. and Water Resour. Rep. KH–R–1, 39 p.

Appendix: Derivation of Friction Factors for Flow in Sand-Bed Streams by the Alam-Kennedy Procedure

The following procedure was used to determine depth-discharge relationships for the problem described on pages 4–24 to 4–26. The procedure is empirical and is designed to reflect the influence of variable bed roughness on flow and thus on sediment transport. The hydraulic conditions were described briefly on pages 4–8 and 4–9. By comparing observed depth-discharge relationships with predicted relationships, Alam and Kennedy (1969) demonstrated that the procedure applies to the full spectrum of bed forms. They considered depth equivalent to hydraulic radius, an assumption that must be adjusted for channels having substantial differences between the two factors. In addition, the effect of bank roughness should be evaluated.

As illustration of the Alam-Kennedy procedure, the computations for deriving depth-discharge curves are given in the following example. These curves were used to determine sediment transport (tables 4–2 and 4–4) for the Colby method with the Alam-Kennedy technique.

As in the problem presented on pages 4–24 to 4–26, the bank influence is assumed to be negligible so that the hydraulic radius (R) is assumed to be equal to the hydraulic radius with respect to the bed (R_b).

Given:

$$\text{channel slope} = 0.002 \text{ ft/ft}$$

$$d_{50} \text{ size of bed material} = 0.3 \text{ mm} = 0.000984 \text{ ft}$$

For a velocity of 3.5 ft/s, calculate the Froude number where

$$F_D = \frac{U}{\sqrt{gd_{50}}} = \frac{3.5}{0.178} = 19.66$$

Assume $R_b = 1.30$ ft

$$\frac{R_b}{d_{50}} = \frac{1.30}{0.000984} = 1321$$

$$\nu = 1.22 \times 10^{-5} \text{ ft}^2\text{/s (for } 60^\circ \text{ F)}$$

$$R_N = \frac{UR_b}{\nu} = \frac{3.5(1.3)}{1.22 \times 10^{-5}} = 3.73 \times 10^5$$

From figure 4–15, using the values of $U/\sqrt{gd_{50}}$ and R_b/d_{50}, obtain f_b'' (Darcy-Weisbach bed-form friction factor):

$$f_b'' = 0.025$$

From figure 4–16 (Lovera and Kennedy 1969) obtain f'_b (flat-bed friction factor), using the values of R_N and R_b/d_{50}:

$$f'_b = 0.017$$

The total friction factor, f_b, $= f'_b + f''_b = 0.017 + 0.025 = 0.042$.

Calculate the hydraulic radius:

$$R_b = f_b \frac{U^2}{8gS} = \frac{0.042(3.5)^2}{8g(0.002)} = 1.00$$

Because the calculated and assumed values differ by an excessive amount, repeat the preceding steps, using the new value of R_b:

$$\frac{R_b}{d_{50}} = \frac{1.00}{0.000984} = 1{,}016$$

$$R_N = \frac{UR_b}{\nu} = \frac{3.5(1.00)}{1.22 \times 10} = 2.87 \times 10^5$$

From figure 4–15, $f''_b = 0.0215$. From figure 4–16, $f'_b = 0.020$. Then $f_b = f'_b + f''_b = 0.020 + 0.0215 = 0.0415$

$$R_b = f_b \frac{U^2}{8gS} = \frac{0.0415(3.5)^2}{8g(0.002)} = 0.987$$

Because the difference between the calculated and last assumed value of R_b is less than 2 percent, additional computation is unjustified.

$$R_b = 1.00$$

$$U = 3.5$$

$$q = R_bU = 3.5 \text{ ft}^3/(\text{s} \cdot \text{ft})$$

These steps were repeated for velocities between 1.0 and 7.0 ft/s to provide data for the R_b-velocity curve in figure 4–17. The R_b-discharge curve in figure 4–17 was then plotted. Both curves were then used in the derivations of the Colby procedure to yield sediment transport data shown in tables 4–2 and 4–4.

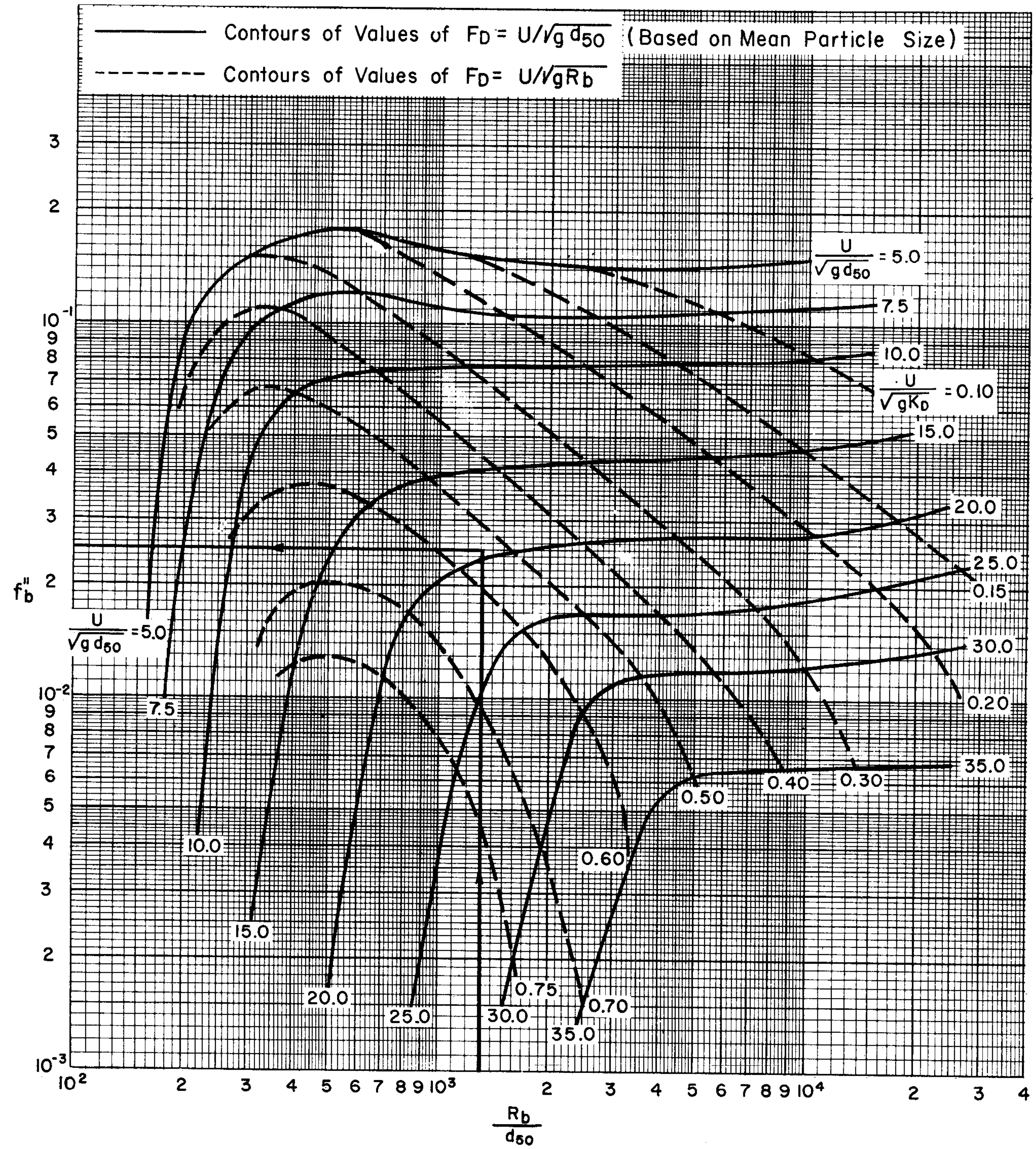


Figure 4-15.—Form-drag friction factor in sand-bed channels, f_b'', as a function of R_b/d_{50} and $F_D = U/\sqrt{gd_{50}}$. From Alam and Kennedy (1969), American Society of Civil Engineers (1975, p. 142).

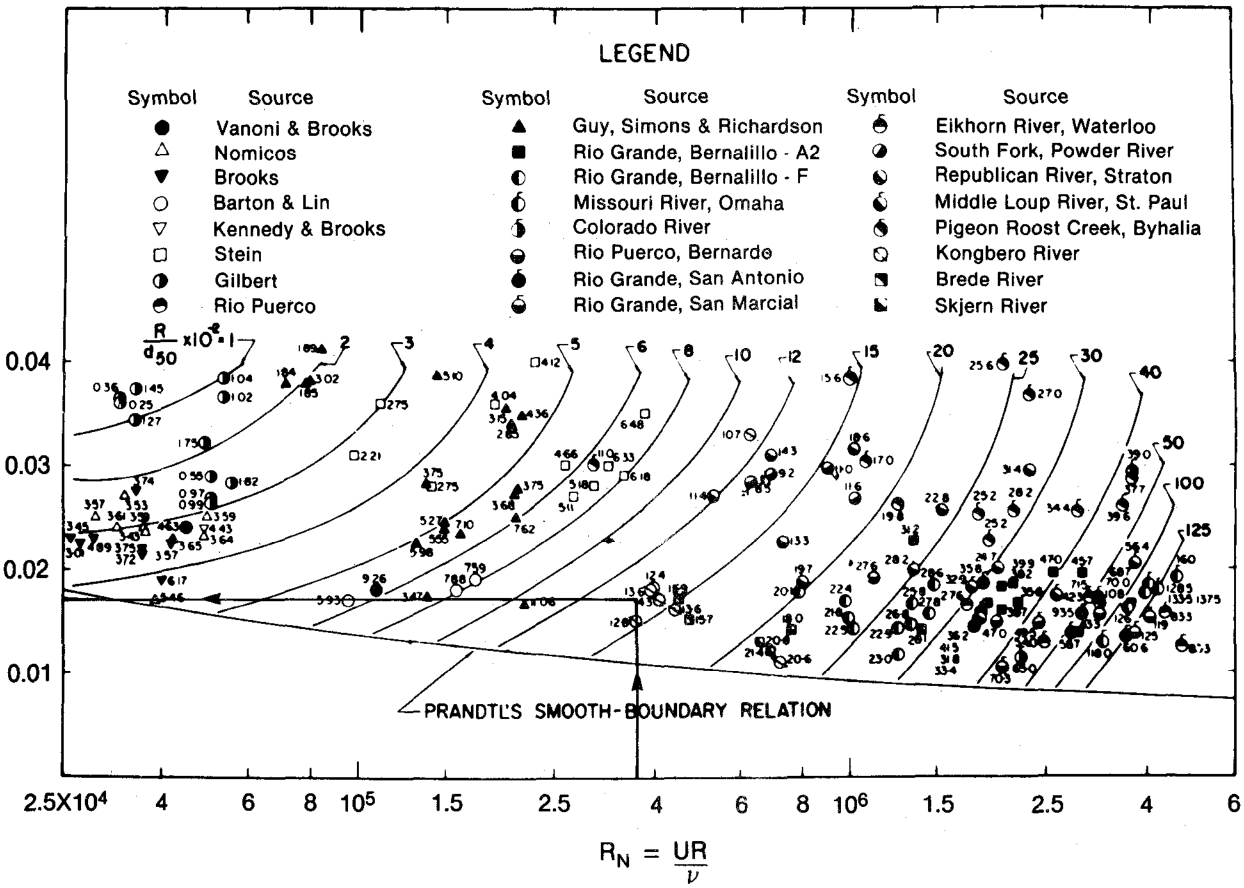


Figure 4–16.—Friction-factor predictor for flat-bed flows in alluvial channels. The number by each point is $R/d_{50} \times 10^{-2}$. From Lovera and Kennedy (1969), American Society of Civil Engineers (1975, p. 140).

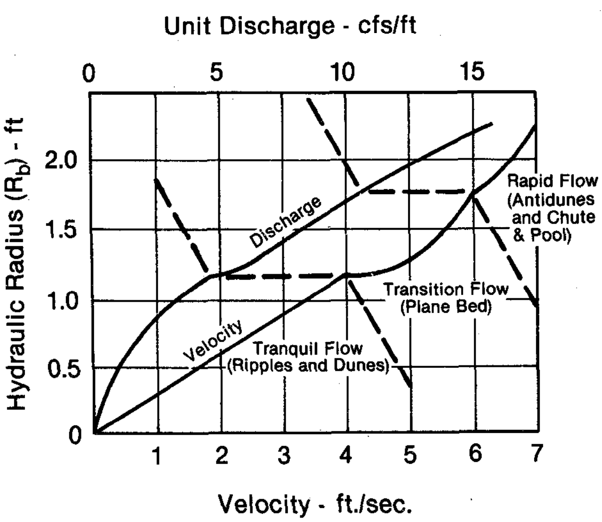


Figure 4–17.—Depth-discharge relationships obtained by Alam-Kennedy technique.

United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Chapter 5

Deposition of Sediment

Contents

	Page
General	5-1
Fan deposition	5-2
Occurrence	5-2
Identification	5-2
Procedures for determining physical damage	5-2
Colluvial deposition	5-4
Flood-plain deposition	5-4
Occurrence	5-4
Vertical-accretion deposits	5-4
Flood-plain splays	5-5
Other deposits	5-5
Identification	5-5
Texture	5-5
Color	5-5
Compaction	5-5
Distinctive minerals	5-5
Evidence of cultural activity	5-5
Stratification	5-5
Procedures for determining the extent of deposition	5-5
Channel deposition	5-7
Occurrence	5-7
Identification	5-7
Channel-fill deposits	5-7
Valley-plug deposits	5-7
Lateral-accretion deposits	5-7
Procedure for determining physical damage	5-7
Association of flood-plain and channel deposits	5-7
Sediment deposits in reservoirs	5-11
Character and distribution	5-11
Volume-weight	5-11
Procedure for determining cost of damage	5-11
Sediment deposits in harbors and estuaries	5-14
Occurrence	5-14
Identification	5-14
Procedures for determining physical damage	5-14
References	5-17

Figures

Page

5–1. An alluvial fan, Okanogan County, Wash 5-3
5–2. Vertical accretion, subsoil over topsoil in creek bottom, Fairfield County, Ohio 5-6
5–3. Channel fill, lateral and vertical accretion, Winona County, Minn. 5-8
5–4. Coarse channel fill, Salt Creek, Iron County, Utah. 5-9
5–5. Examples of sediment distribution in reservoirs 5-12
5–6. Reservoir sediment accumulation, Lake Accotink, Fairfax County, Va 5-13
5–7. Filled estuary at Joppa Town, Md. 5-15

Tables

Page

5–1. Characteristics of genetic types of valley deposits 5-10

Chapter 5
Deposition of Sediment

General

This chapter describes various types of sediment deposits and the physical damage they cause.[1] SCS geologists identify many types of sediment deposits, determine their rates of deposition, and compare these rates with natural or geologic rates of deposition. Such investigations are concerned chiefly with sediment deposits on flood plains and in channels and reservoirs. The deposits are discussed in the general sequence in which they occur from the uplands to the sea.

Kinds of physical damage commonly caused by sediment deposition are:

1. Burial of fertile soils by less fertile sediment.
2. Damage to growing crops and burial of crops.
3. Impairment of drainage and the accompanying rise of the water table and increase in swampy areas of alluvial land.
4. Filling of channels, causing more frequent flooding and increased flood heights. Filling may change the course of the channel.
5. Filling of reservoirs and debris basins.
6. Damage to railroads, bridges, roads, powerlines, and other facilities. Ditches and roads may be filled enough to need regrading.
7. Damage to urban areas from sedimentation and increased flood heights.
8. Damage to recreation facilities.

The extent of the damages is ordinarily calculated in terms of the degree of possible restoration to original conditions or the extent of the loss of productivity or services. Geologists and economists work closely together to determine the damage. Geologists obtain information on the physical damage and economists figure the costs on the basis of this information.

Occurrence

A typical alluvial fan is an accumulation of sediment carried by a stream descending through a steep ravine or canyon. When the stream emerges from this confined area, it loses velocity and drops most of the sediment, which spreads out in the shape of a fan. The fan is roughly semiconical, with the apex at the canyon end. The materials composing an alluvial fan range in size from fines to boulders. The streams supplying debris to fans are agents of vigorous erosion, and they commonly transport an enormous volume of sediment. Boulders, cobbles, and gravel are deposited at the upper end of a fan, and the finer sands, silts, and clays are carried to lower elevations (fig. 5–1).

Much of the stream water percolates through the porous coarse material in the fan. The spreading of streamflow and the loss of water through percolation cause deposition of the entire sediment load. The steepness and size of alluvial fans vary with the geology, climate, and watershed size. Fan deposits range from wide fans of moderate slope (4 to 6 degrees) to relatively steep cones (as much as 15 degrees) built of coarse debris transported by short torrential streams (Holmes 1965).

Streams on a fan characteristically change course frequently and develop a series of distributaries. Fans may be isolated or they may coalesce to form a long, broad alluvial slope. The development of many fans is characterized by erratic and sudden depositional events, especially in arid and semiarid climates. Long periods of quiescence may be ended by heavy rains producing torrential flows. The volume of sediment deposited on fan areas below mountain slopes and canyons after a single heavy rain can be enormous. Deposits along mountain fronts in the United States are important because many of them are in agricultural or urban areas and are present difficult problems.

Damage caused by sediment-laden flows ranges from disasters following severe storms to relatively minor incidents following more frequent smaller storms. Many fans are forming at the foot of valley slopes in the Central Lowlands and even in the rougher parts of the Coastal Plains.

Identification

Fan deposition is not limited to mountain environments. The composition of all fan deposits closely resembles that of the parent rock, since relatively little chemical weathering has taken place. The coarse-textured sediment ranges from angular to round, depending on the distance moved and the resistance of the rock to abrasion. The coarser sediment of a fan is deposited near the top (apex) of the fan, where the slope is usually steepest. Near the base of the fan, where the slope decreases, the grain size also decreases. Bedding is not distinct or regular, however, in fan deposits.

Procedures for Determining Physical Damage

The study of damage caused by fan deposition should begin with preparation of a map showing the area affected. The map should show the chief features of concern (drainage, topography, and sediment sources), and the fan areas should be drawn to scale.

A survey to determine the volume, texture, and depth of the deposit will yield measurements of the fan and its associated damages. The survey can be coordinated with a system of ranges to obtain cross sections of the valley. The ranges in the fan area should be spaced closely enough to show more detail. Borings along the cross sections or ranges can help identify possible buried old soil horizons, although borings may not provide conclusive information at many points in the fan. The great thickness and coarseness of many fans may make measurements by boring impractical. For data on annual damages and volume of deposition, the investigation should be supported by the best historical records obtainable.

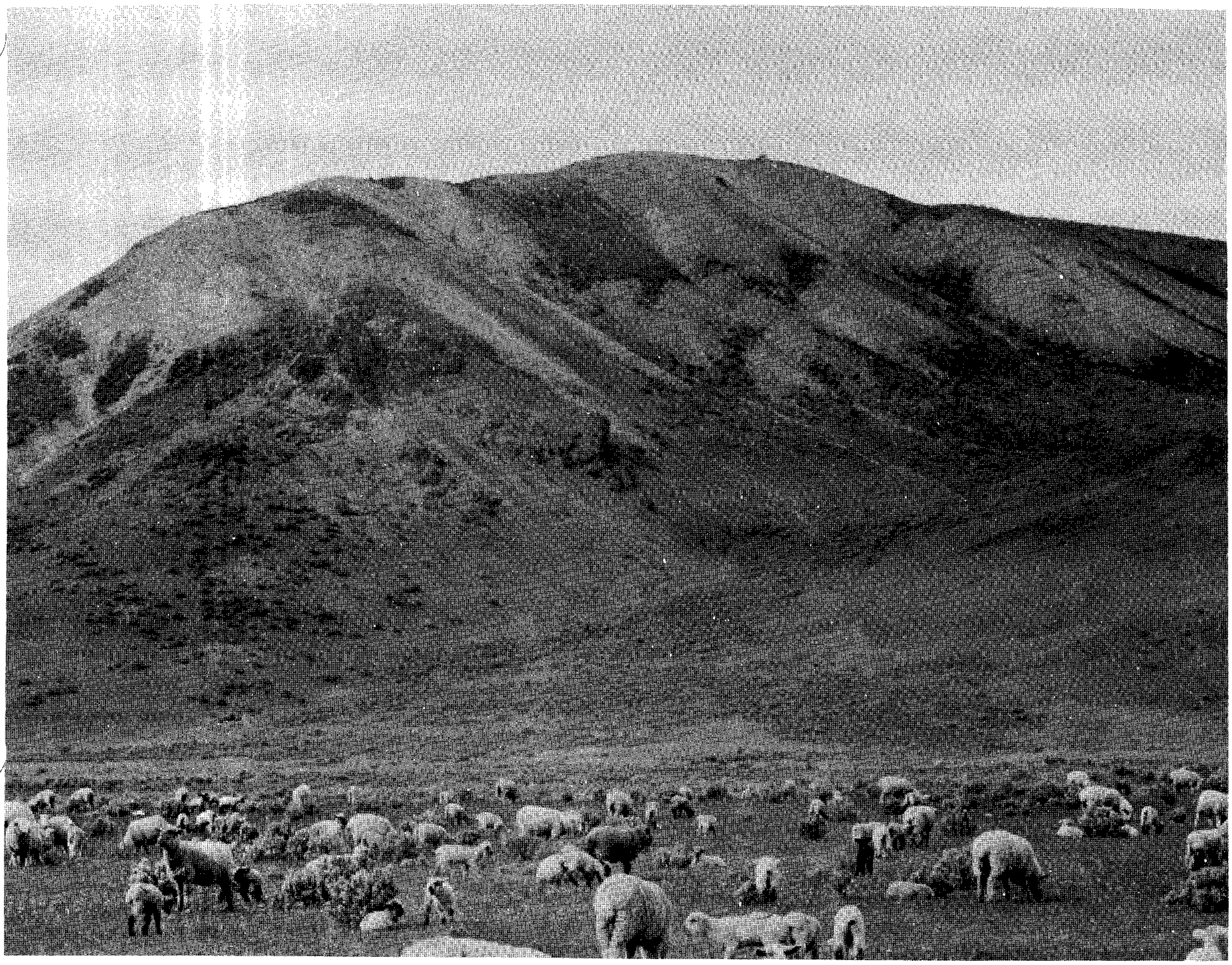


Figure 5-1.—An alluvial fan, Okanogan County, Wash.

Colluvial Deposition

Colluvial deposits are products of upland erosion that are moved by gravity, mass movement, or unconcentrated surface runoff; they commonly accumulate on the lower part or base of slopes. They represent some of the products of erosion that do not reach stream channels, reservoirs, or other points where sediment quantity and movement usually are measured. Colluvial deposits tend to accumulate where upland slopes decrease, which may be at the foot of a slope or wherever the transporting power of the overland flow is lessened. Upland colluvial deposition is thus closely related to sheet erosion. Colluvial deposits characteristically are narrow bands of sediment deposits having linear or sinuous shape. A reasonably complete survey of an area provides information on the approximate volume of colluvial deposits. This volume can then be subtracted from the calculated total erosion to determine sediment yield to an area farther downstream. The history of land use and cultivation in the area can provide a basis for calculating the annual contribution to the colluvial deposits.

The extent of damage caused by colluvial deposits varies widely. The basis of all damage estimates should be:

1. A map showing the extent of the area.
2. Borings for volume and rate of deposition, supported by local history.
3. Determination of the nature of the sediment and its effects.

Flood-Plain Deposition

Occurrence

A flood plain is a strip of relatively smooth land that borders a stream and is covered with water when the stream overflows (Leopold, Wolman, and Miller 1964). Flood plains range from a few feet to several miles wide.

In a valley where modern sedimentation is widespread, the natural levees, which in many places are dominant features, may be several feet thick. Away from the channel and natural levees the vertical-accretion deposits generally decrease in thickness toward the edges of the flood plain.

Where sedimentation from tributaries and valley slopes has been rapid, alluvial fans and colluvial deposits overlap the edges of the flood-plain deposits. If deposition in the main channel has been excessive, the channel may have become filled and its bottom elevation may be higher than the surrounding flood plain. Subsequent flood flows may then follow an entirely different course. In some valleys, modern sedimentation has substantially damaged the flood plain but has not formed a continuous valley-wide deposit.

The following descriptions of flood-plain deposits are after Happ, Rittenhouse, and Dobson (1940).

Vertical-Accretion Deposits

In times of flood, stream channels lack the capacity to carry all the water delivered to them as surface runoff. The excess water overflows the banks and spreads over the adjacent flood plain. Because of greater frictional resistance, this spreading markedly reduces velocity and reduces transporting capacity even more. Part of the sediment that was carried in suspension while the water was confined to the channel is therefore deposited on the flood plain. As velocity decreases, the coarse material is dropped first and builds up the characteristically sandy natural levees that border the channels. The finer sediment is carried farther from the channel and deposited as a thin layer over the entire flood-plain surface. This is the process of vertical accretion, and the deposits are composed almost entirely of sediment carried to the place of deposition as suspended load. In this respect vertical-accretion deposits differ from channel deposits, which are largely composed of bedload sediment (fig. 5–2).

Flood-Plain Splays

The regularity of flood-plain deposition is interrupted where excess water leaves the channel through restricted low sections or breaks in the natural levees. In such places the velocity of the escaping water may be high enough to carry an appreciable amount of relatively coarse sediment farther from the channel than would otherwise happen. The sand and gravel sediment is commonly spread outward in a fan shape on the flood plain, across which it is moved forward at least partly as bedload. The resulting deposits are flood-plain splays.

Other Deposits

Colluvial deposits occur on flood-plain borders at the base of slopes. They are composed of material moved by gravity, mass movement, and sheet erosion.

Older channel deposits underlie much of the flood plain. Channel-fill deposits, lateral-accretion deposits, and valley-plug deposits are described under channel deposition.

Identification

Identifying deposits formed by modern accelerated deposition depends chiefly on the ability to distinguish between modern sediment and the buried original flood-plain soil. Since the characteristics of both the sediment and the buried soils may differ in different valleys, their relationships must be investigated when beginning a valley survey. The important criteria for differentiating modern sediment from buried soil are as follows:

Texture

Modern sediment is usually coarser and varies more in texture than buried soil.

Color

Modern sediment is usually a light color that may vary with texture; buried soil is usually darker and more uniform in both color and texture. Modern sediments may have a gray or greenish-gray staining as a result of a formerly high ground-water table.

Compaction

Modern sediment is often less compact and less cohesive than buried soil.

Distinctive Minerals

Modern sediment may contain grains of gypsum, feldspars, calcite, or other easily weathered minerals. Very few grains of easily weathered minerals occur in buried soil. Buried soil usually contains more clay minerals than modern sediment.

Evidence of Cultural Activity

Modern sediment may cover or contain boards, tools, bricks, fences, other manmade objects, and tree stumps.

Stratification

In many places modern sediment has distinct stratification with crossbedding and lenticular beds.

Procedures for Determining the Extent of Deposition

A survey of a watershed area should include a study of all important valleys. Information bearing on erosion rates, sediment yield, and flooding should be summarized. Summaries should include valley width and depth, nature of the slopes, chief rock outcrops, nature and extent of terraces and their relationships to channels. These features all directly influence the nature and magnitude of the sediment deposits (Roehl and Holeman 1975).

Figure 5–2.—Vertical accretion, subsoil over topsoil in creek bottom, Fairfield County, Ohio.

Occurrence

Sediment is deposited in channels in many situations and environments, including alluvial fans, large river valleys, distributaries and passes of deltas, and alluvial plains. Deposits resulting from channel fill and lateral accretion can be found throughout any flood plain (fig. 5–3).

Identification

An accumulation of sediment in a channel results from the inability of the stream to carry all its load. The process of accumulation has been described by Happ, Rittenhouse, and Dobson (1940); Brown (1950); Einstein (1950); Leopold, Wolman, and Miller (1964); Happ (1975); and others. Generally, the coarsest sediment is deposited in and along the channel. The channel may be partly or completely filled, so that future flows follow an entirely different course. Channel deposits can be identified by their coarse texture and sinuous shape and by the damage caused, such as filled channelways and bridge openings and new areas of swamping.

Channel-Fill Deposits

These deposits occur in stream channels where the transporting capacity has been insufficient to remove the sediment as rapidly as it has been delivered. The process is not a simple sorting out and deposition of the coarsest material but consists of a net accumulation of material from alternating scour (during rising flood stages) and deposition (during the falling stages). If the average amount of scour is less than the average amount of deposition, the net result is aggradation of the channel bed. Channel deposits are generally coarse textured (fig. 5–4).

Valley-Plug Deposits

These deposits are always associated with filling of the stream channel. When the channel has been completely filled in one place, the area of deposition moves upstream by backfilling. At the same time, the water flowing in the channel is forced overbank, draining down the valley as through back-swamp areas, until it again collects into definite channels and eventually returns to the main channel.

Plugs are caused by a decrease in the transport capacity of the stream channel. The channel capacity can be decreased by fallen trees and jams of driftwood, by delivery of sediment from a tributary in quantities that completely choke the main stream channel, or by inadequate artificial channel modification downstream. The cause of the original channel obstruction may not be evident.

Lateral-Accretion Deposits

These deposits form along the sides of channels, where bedload material is moved by traction toward the inner sides of channel bends. Normally, such deposits of lateral accretion are later covered by finer material of vertical accretion as the channel shifts farther away from its former course by lateral bank cutting. The old slip-off slope on the inside of the bend then is overflowed less frequently and with lower velocity.

Procedure for Determining Physical Damage

The quantity of and damage from channel deposits should be measured by borings to determine thickness, by mapping to determine extent, and by reviewing the most recent records available to determine frequency of deposition. Information on clearing of sediment from channels and under bridges, as well as from road surfaces, is often available in county engineers' offices and can be used as one measure of the damage caused by channel action. The information gathered may include:

1. Volume of channel and bridge clearing.
2. Depth and area of places where channel action has raised the water table.
3. Amount of increase in the flood hazard and damage, which can be investigated and evaluated along the ranges of the watershed survey.

Association of Flood-Plain and Channel Deposits

In the normal flood-plain association of sediments, vertical-accretion deposits cover coarse lateral-accretion and channel-fill deposits. Vertical-accretion deposits cover the flood plain with a layer of fine sediment fairly uniform in thickness that slopes away from the channel to the valley sides. Vertical-accretion deposits are the chief sources of

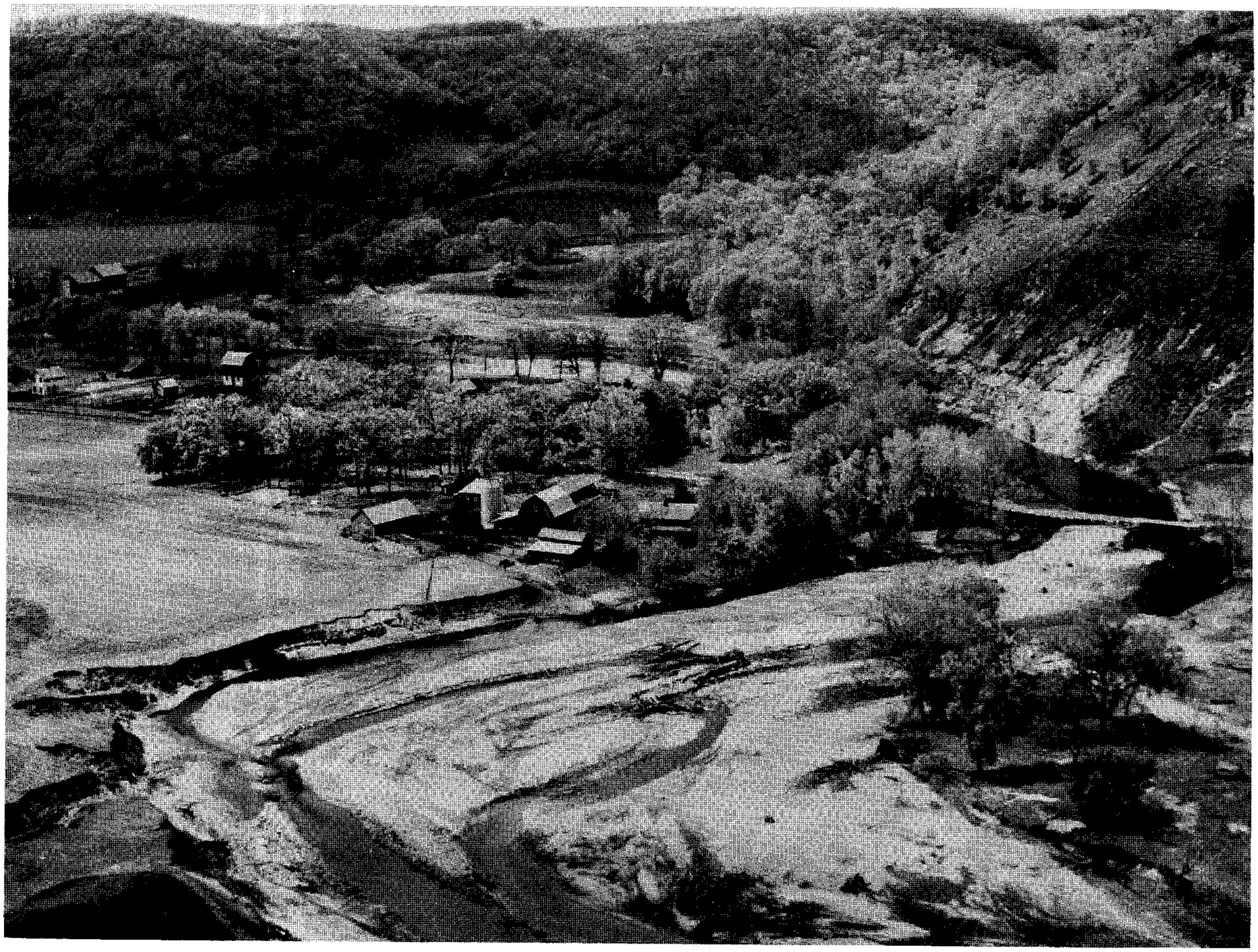


Figure 5–3.—Channel fill, lateral and vertical accretion, Winona County, Minn.

the fertile bottom land in most valleys.

Modern channel-fill deposits occur in the present channel and in abandoned channels. They may be covered by vertical-accretion deposits in the abandoned channels. Sand splays occur immediately alongside present or former channels and interfinger into the vertical-accretion deposits. Colluvial and fan deposits interfinger into the vertical-accretion deposits from the valley sides. The characteristically low area between the natural levees and the colluvial deposits is called the backswamp part of the flood plain. Characteristics of the different types of deposits in the normal flood-plain association are summarized in table 5–1.

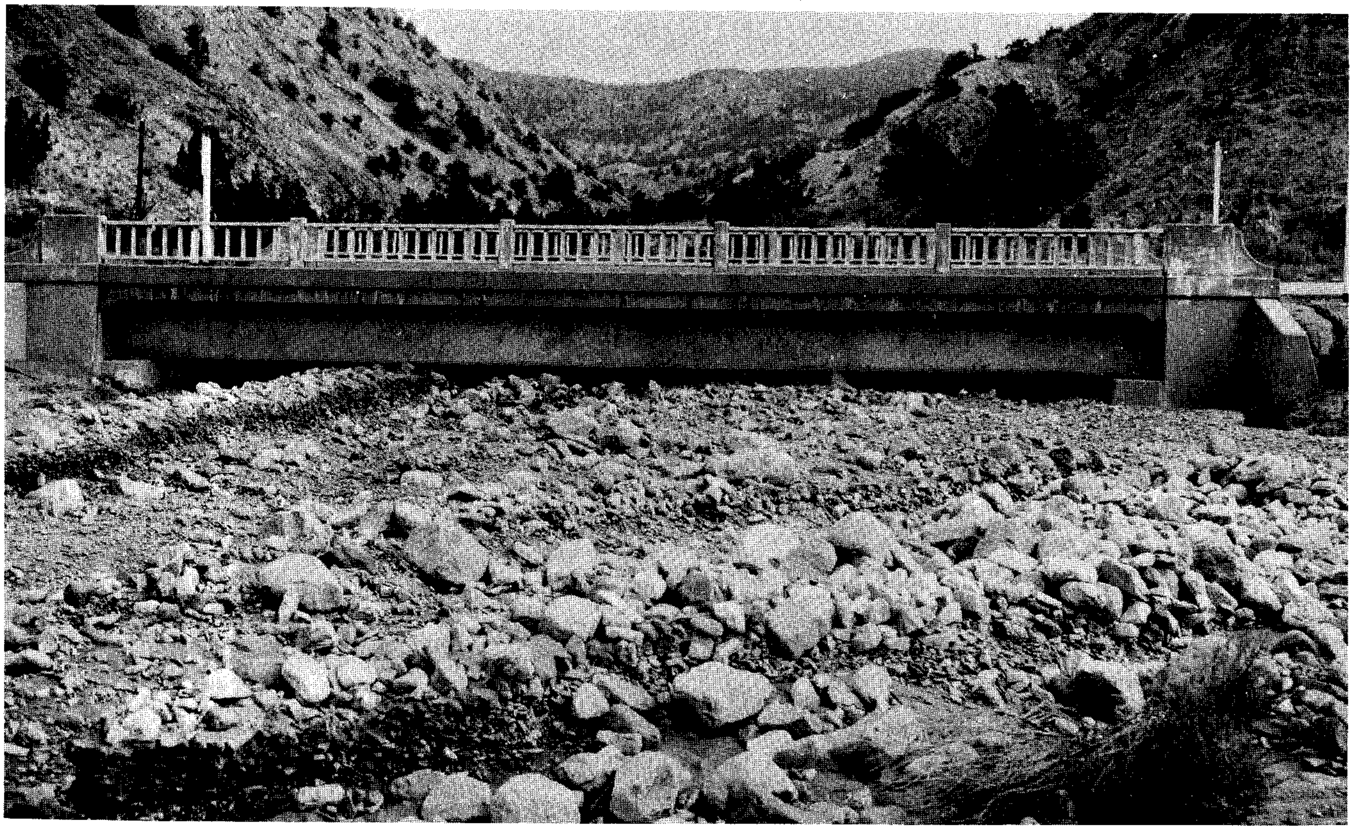


Figure 5–4.—Coarse channel fill, Salt Creek, Iron County, Utah.

Table 5–1.—Characteristics of genetic types of valley deposits

		Fluvial deposits			
Characteristic	Colluvial deposits	Vertical accretion	Splays	Lateral accretion	Channel fill
Principal origin	Concentration by slope wash and mass movements	Deposition of suspended load	Deposition of bedload	Deposition of bedload always prominent, but suspended load may be dominant	Deposition of bedload and suspended load
Usual place of deposit	At junction of flood plain and valley sides	On entire flood-plain surface	On flood-plain surface adjacent to stream channel	Along side of channel, especially on the inside of bends	Within the channel
Dominant texture	Range from silty clay to boulders	Dominantly silt; often sandy, especially near channel; often much clay	Usually sand; may be gravel or boulders	Sand or gravel; may include silt or boulders	Usually sand, silt, and gravel; may include clay or boulders
Relative distribution in the valley fill	Interfinger with the fluvial deposits along outer margins of flood plain	Overlie lateral accretion and channel deposits; overlain by or interbedded with splay and colluvial deposits; usually cover most of flood-plain surface	Form scattered lenticular deposits overlying or interbedded with vertical accretion deposits adjacent to present or former channels	Usually underlie vertical-accretion deposits, often overlie channel-fill deposits; may extend across entire flood-plain width	Usually form elongate deposits of relatively small cross section winding through flood plain; may underlie vertical-accretion deposits

Only a general description of sediment deposits in artificial basins is presented in this chapter. Additional details on reservoir sedimentation are given by many investigators, including Stevens (1936); Eakin (1939); Noll, Roehl, and Bennett (1950); Holeman and Geiger (1959); and Gottschalk (1975). Methods for measuring and evaluating sedimentation in reservoirs are discussed in other parts of this section, including Chapter 6, Sediment Sources, Yields, and Delivery Ratios; and Chapter 7, Field Investigations and Surveys.

Character and Distribution

Sediments deposited in impounding reservoirs designed to keep fluctuations in the water level to a minimum have a typical texture and distribution. The bulk of the deposit consists of clay and silt particles distributed fairly evenly over the reservoir bottom. The coarser particles (sand, gravel, and boulders) are deposited in or near the head of the impounded pool, where the velocity of inflowing currents is reduced. The silt and clay particles remain in suspension longer and are spread widely over the reservoir bottom. Some sands, gravels, and poorly sorted deposits may occur in relatively narrow shore zones, especially if wave erosion has been active. The composition and texture of beach deposits depend on the nature of the shore (Jones and Roger 1952; Jones, Renfro, and Commons 1954).

If the water level in a reservoir fluctuates widely, the character and distribution of the sediment deposit change considerably. When a large withdrawal of water coincides with a period of drought, the water in the pool may fall to a very low level or the reservoir may be completely drained. When exposed to air, the clay and silt deposits become partly desiccated and shrink, thereby increasing the capacity of the resevoir. Repeated surveys by SCS have documented this behavior; for example, the capacity of Lake Medina in Texas has been partly restored in this manner at least three times.

In contrast to the broad uniform distribution of sediment in many impounding reservoirs, some deposited sediment may be redistributed by sudden large inflows occurring during or after periods of low water level. The upstream parts of the channels may be scoured, and course sediment from the upstream segments may be transported downstream and deposited in areas previously occupied only by clays and silts. This has occurred repeatedly in reservoirs such as Lakes Abilene, Nasworthy, and Waco in Texas and in larger impoundments such as Alamagordo and Elephant Butte Reservoirs and Lake Texoma. The coarse texture of the incoming sediment tends to concentrate deposition around the head of the reservoir. Careful study of the deposits during a reservoir survey can yield many data about the sources and formation of the reservoir deposit. Figure 5–5 shows typical distribution of sediment in reservoirs; figure 5–6 shows excessive accumulation of sediment.

Volume-Weight

The volume-weight of a substance is its weight per unit volume. It is also called dry density or specific weight. This important property of sediment is discussed in Chapter 2, and data are presented there on the volume-weight of reservoir sediment. In general, sediments are compacted by heavy overlying loads, aging, and loss of water. The volume-weight of sediment is affected by the operation of the reservoir and by the sorting and composition of the sediment. Generally, soils and rocks occupy more space after deposition in a reservoir than they did in place in a watershed. This phenomenon has been investigated by Brown and Thorp (1947), Gottschalk and Brune (1950), Jones and Roger (1952), Glymph (1954), Koelzer and Lara (1958), Lara (1970), and others. The sediment occupies 1.1 to about 1.4 times the volume of the same soil in place in the watershed.

Procedures for Determining Cost of Damage

Sediment damage to reservoirs is usually evaluated by SCS economists, who use one of four methods: (1) straight line, (2) sinking fund, (3) sinking fund plus loss in service, and (4) cost of sediment removal. These methods are also used by SCS economists to determine the monetary benefits derived from recommended soil conservation programs (Soil Conservation Service 1964). Geologists should work closely with economists to determine the type of economic analysis to be made and the

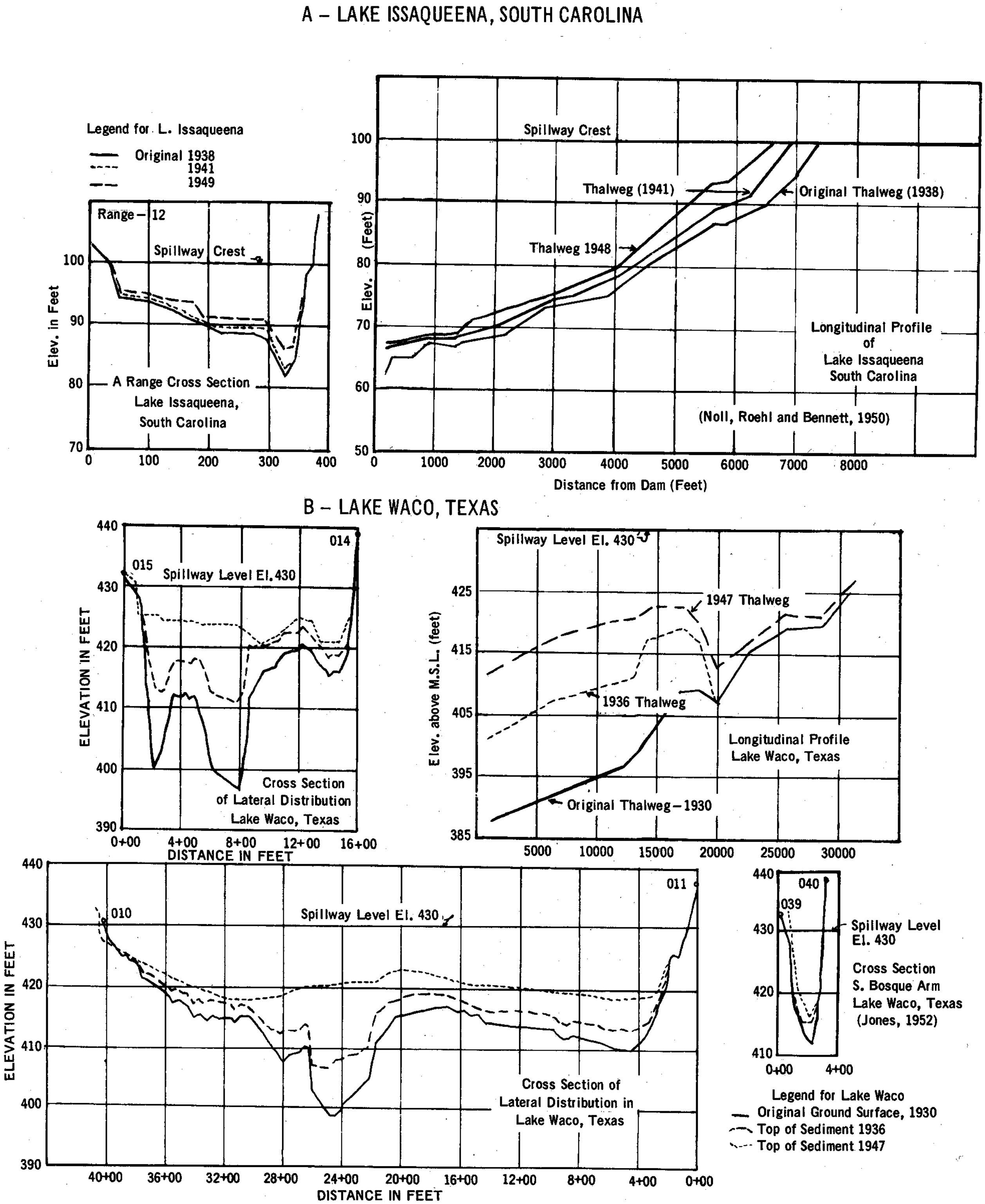


Figure 5–5.—Examples of sediment distribution in reservoirs.

Figure 5–6.—Reservoir sediment accumulation, Lake Accotink, Fairfax County, Va.

kind of field data needed for the specific analysis proposed.

In the straight-line method, the estimated average annual damage is the product of the average annual rate (in acre-feet) of storage loss from sedimentation times the original cost per acre-foot of storage. Geologists must determine the average volume of sediment expected to be deposited annually, with and without installation of the recommended conservation program. For evaluating sediment damage to existing reservoirs the annual rate of sediment deposition can be determined from a reservoir survey, as described in Chapter 7. The future rate of sediment deposition after completing the recommended soil conservation program can be determined by the methods described in Chapter 8 for the design of proposed reservoirs.

The sinking-fund and the sinking-fund plus loss-in-service methods of evaluation are used when the available information clearly indicates that a reservoir will be replaced before there is any significant loss in service. In these methods, the useful life of the structure, with and without the recommended soil conservation program, and the average annual rate of sediment accumulation must be determined.

Evaluating reservoir sedimentation damages on the basis of cost of sediment removal requires estimating sediment yield and the average amount of sediment to be removed annually, with and without the recommended program. This method is used when information indicates that reservoir storage capacity can be maintained by removal of the sediment.

The method selected to evaluate damage to a reservoir depends on the amount of information that can be obtained within the limitations of time and budget and the importance of the benefits accruing from a reduced rate of sediment accumulation. The straight-line method is simple to use and is the preferred method (Soil Conservation Service 1964, p. 5–20).

Sediment Deposits in Harbors and Estuaries

Occurrence

Tides and river discharge intermingle fluvial and beach deposits so that they are heterogeneous in both character and distribution. One of the chief problems affecting the use and maintenance of harbors is sediment accumulation in their basins and channels. Costly dredging and other measures are necessary to maintain ship channels and docking facilities. Accelerated upland erosion and the resulting increased sediment loads have greatly increased deposition in harbors since agriculture and industry developed in the United States. Many records of this increase in deposition are available (e.g., fig. 5–7).

Identification

Identifying the deposits in harbors and estuaries requires investigating both the sediment transported into the area by streams and the sediment produced by erosion of the shores and the reentrants of the bays under investigation. Minerals occurring along the shores or transported into the area may be so distinctive that they can be identified in the shore or outer bay deposits. If these minerals can be identified and traced, some data can be assembled on the relative importance of the sources of the sediment. This mineralogical relationship can also be used to determine the sediment contributed from industrial plants and other sources in the area.

Procedures for Determining Physical Damage

The SCS has investigated sedimentation in some harbors. Brown, Seavey, and Rittenhouse (1939) reported on deposits in the York River estuary in Virginia. Holeman (1962) reported that 141,000,000 yd^3 of sediment had been removed from Baltimore Harbor between 1836 and 1960 by federal agencies at a cost of $26 million. Reports of the U.S. Army Corps of Engineers, including annual reports by the Chief of Engineers and those of the district offices, are good sources of information on sediment removed by dredging. A comparison of maps or aerial photographs made years apart of harbors and estuaries not subject to dredging may indicate the rate of sediment accumulation (fig. 5–7).

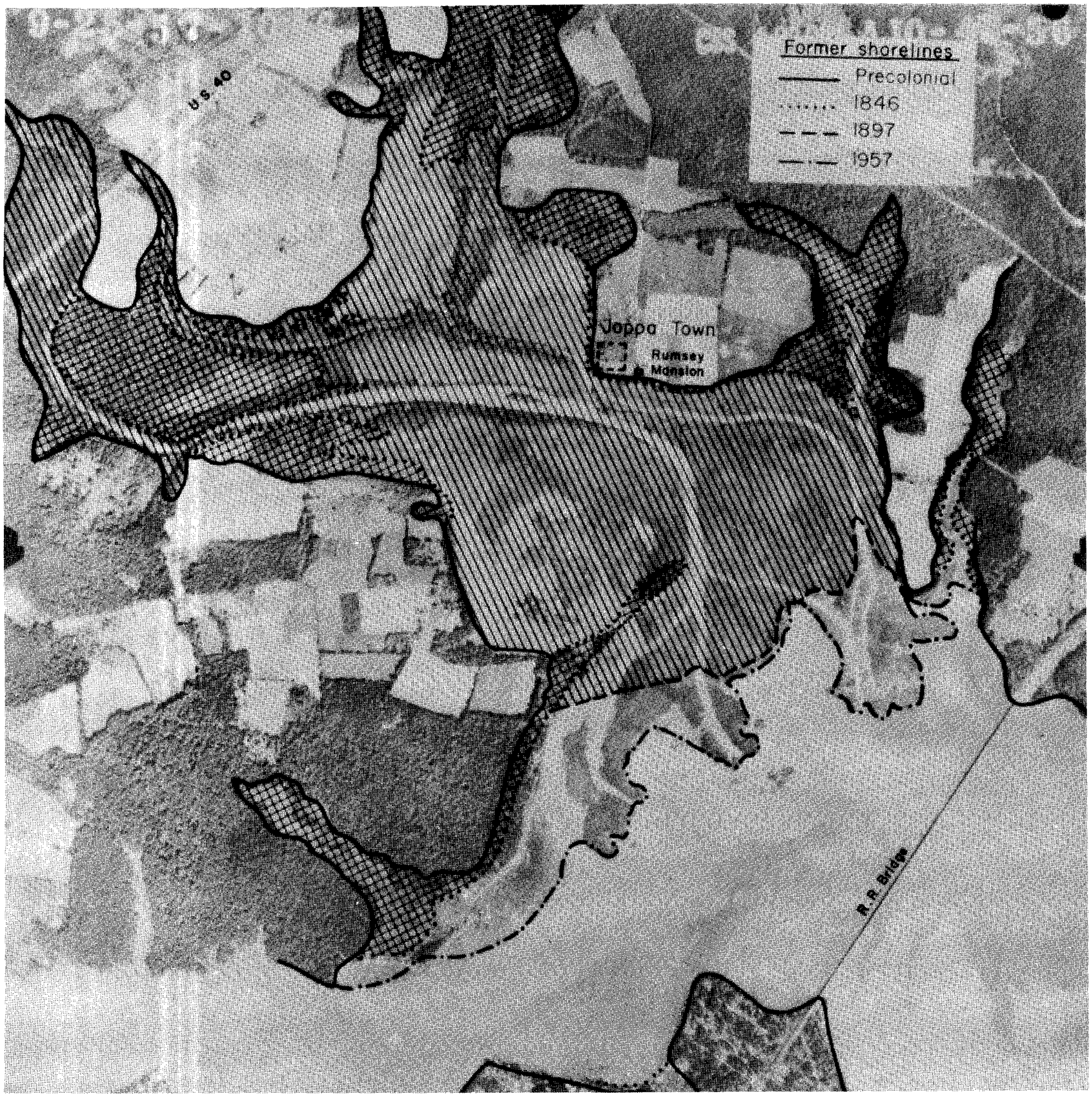


Figure 5–7.—Filled estuary at Joppa Town, Md.

References

Brown, Carl B. 1950. Sediment transportation. *In* Engineering hydraulics, ch. 12, p. 769–857. Hunter Rouse, ed. John Wiley & Sons, Inc., New York.

Brown, Carl B., Louis M. Seavy, and Gordon Rittenhouse. 1939. Advance report on an investigation of silting in the York River, Va. USDA Soil Conserv. Serv. SCS–SS–32, 12 p.

Brown, Carl B., and E. M. Thorp. 1947. Reservoir sedimentation in the Sacramento-San Joaquin drainage basins, California. Soil Conserv. Serv. Spec. Rep. 10, 69 p.

Brune, Gunnar M. 1953. Trap efficiency of reservoirs. Am. Geophys. Union Trans. 34(3): 407–418.

Eakin, H. M. 1939. Silting of reservoirs, revised by C. B. Brown. U. S. Dep. Agric. Tech. Bull. 524, 168 p.

Einstein, Hans A. 1950. The bed-load function for sediment transportation in open-channel flows. U. S. Dep. Agric. Tech. Bull. 1026.

Gilluly, J., A. C. Waters, and A. O. Woodford. 1968. Principles of geology. 3d ed. W. H. Freeman & Co., San Francisco, Calif., 687 p.

Glymph, Louis M., Jr. 1954. Studies of sediment yields from watersheds. Int. Union of Geod. and Geophys., Int. Assoc. Hydrol. 10th Gen. Assem., Rome, Italy, Part 1, p. 178–191.

Gottschalk, L. C. 1965. Trap efficiency of small floodwater-retarding structures. Am. Soc. Civ. Eng. Water Resour. Eng. Conf., March 8-12, Mobile, Ala. Conf. Prepr. 147.

Gottschalk, L. C. 1975. Nature of sedimentation problems. *In* Sedimentation engineering, ch. 1, p. 1–16. Vito A. Vanoni, ed. Manuals and Reports on Engineering Practice No. 54, Am. Soc. Civ. Eng., New York.

Gottschalk, L. C., and G. M. Brune. 1950. Sediment-design criteria for the Missouri Basin loess hills. USDA Soil Conserv. Serv. Tech. Publ. 97.

Happ, Stafford C. 1975. Genetic classification of valley sediment deposits. *In* Sedimentation engineering, ch. 2, p. 286–292. Vito A. Vanoni, ed. Manuals and Reports on Engineering Practice No. 54, Am. Soc. Civ. Eng., New York.

Happ, Stafford C., Gordon Rittenhouse, and G. C. Dobson. 1940. Some principles of accelerated stream and valley sedimentation. U. S. Dep. Agric. Tech. Bull. 695, 134 p.

Holeman, J. N. 1962. Conservation helps lick century-old sedimentation bugaboo. Soil Conserv. 27(11):260–262.

Holeman, J. N. 1967. Sediment brings early death by strangulation to colonial port. Soil Conserv. 32(10):223–225.

Holeman, J. N., and A. F. Geiger. 1959. Sedimentation of Lake Barcroft, Fairfax County, Va. USDA Soil Conserv. Serv. Tech. Publ. 136, 16 p.

Holmes, A. 1965. Principles of physical geology. The Ronald Press Co., New York, 1,288 p.

Jones, Victor H., and Ross E. Rogers. 1952. Aspects of sedimentation in Lake Waco, Waco, Texas. USDA Soil Conserv. Serv. Tech. Publ. 100.

Jones, Victor H., G. W. Renfro, and G. G. Commons. 1954. Problems of sedimentation and water supply in Lake Nasworthy, San Angelo, Texas. USDA Soil Conserv. Ser., Temple, Tex., 26 p.

Koelzer, V. A., and J. M. Lara. 1958. Densities and compaction rates of deposited sediment. Proc. Am. Soc. Civ. Eng., J. Hydraul. Div. 84(HY2), paper 1603, 15 p.

Krumbein, W. C., and L. L. Sloss. 1963. Stratigraphy and sedimentation. 2d ed. W. H. Freeman & Co., San Francisco, Calif., 660 p.

Lara, J. M. 1970. Chapter III. Sediment measurement techniques: reservoir deposits. Proc. Am. Soc. Civ. Eng., J. Hydraul. Div. 96(HY12) :2,417–2,446.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W. H. Freeman & Co., San Francisco, Calif., 522 p.

Noll, J. J., J. W. Roehl, and J. Bennett. 1950. Effect of soil conservation on sedimentation in Lake Issaqueena, Pickens County, South Carolina. USDA Soil Conserv. Serv. Tech. Publ. 95, 20 p.

Roehl, J. W., and J. N. Holeman. 1975. Accelerated valley deposits. *In* Sedimentation engineering, ch. 3, p. 382–385. Vito A. Vanoni, ed. Manuals and Reports on Engineering Practice No. 54, Am. Soc. Civ. Eng., New York.

Soil Conservation Service, U. S. Department of Agriculture. 1964. Economics guide for watershed protection and flood prevention.

Stevens, J. C. 1936. The silt problem. Am. Soc. Civ. Eng. Trans. 101: 207–250.

Trask, P. D., ed. 1950. Applied sedimentation. John Wiley & Sons, Inc., New York, 707 p.

Twenhofel, W. H. 1950. Principles of sedimentation. 2d ed. McGraw-Hill Book Co., New York, 673 p.

United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Chapter 6

Sediment Sources, Yields, and Delivery Ratios

Contents

	Page
Introduction	6-1
General	6-1
Interrelationship of processes	6-1
Sediment sources	6-2
General	6-2
Determining the relative importance of various sources	6-2
Maps and aerial photographs	6-2
Distinctive minerals	6-2
Colluviation	6-2
Procedure	6-2
Sediment yield	6-3
General	6-3
Climatic factors	6-3
Watershed factors	6-3
Size	6-3
Topography	6-4
Channel density	6-4
Soil and cover conditions	6-4
Land use	6-4
Methods of determination	6-5
Gross erosion and the sediment delivery ratio	6-5
Measured sediment accumulation	6-5
Suspended load records	6-6
Predictive equations	6-6
Information sources	6-6
Sediment delivery ratio	6-8
Influencing factors	6-8
Sediment source	6-8
Proximity of sediment sources	6-8
Transport system	6-8
Texture of eroded material	6-9
Depositional area	6-9
Watershed characteristics	6-9
Procedures for estimating the sediment delivery ratio	6-9
Size of drainage area	6-10
Relief-length ratio	6-10
Source-texture analysis	6-10
Source deposition	6-11
Summary	6-12
References	6-13

Figures

Page

6–1. A sedimentrating curve 6-7
6–2. Relationship between drainage area and sediment delivery ratio 6-11

Tables

Page

6–1. Sediment yield from various sources 6-3
6–2. Sediment source and the delivery ratio 6-11

Chapter 6
Sediment Sources, Yields, and Delivery Ratios

Introduction

General

Sediment yield depends on the erosion processes at the sediment source and on the efficiency of the system, that transports the sediment to the point of measurement. The sediment yield usually differs at different locations in a stream system.

Many interrelated factors affect sediment yield. Knowledge of each of these factors is important in:

1. Evaluating downstream sediment damages.
2. Determining the location and extent of sediment sources so that effective controls can be planned and installed.
3. Recognizing the relative contribution of the various sources to present and future sediment yield.
4. Determining the sediment storage requirement for designing proposed structural works of improvement.

This chapter presents several procedures for determining sediment sources, sediment yields, and delivery ratios.

Interrelationship of Processes

Sediment yield depends on gross erosion in the watershed and on the transport of eroded material out of the watershed. Only part of the material eroded from uplant areas in a watershed is carried out of the watershed. Variation in the proportion of the eroded material deposited as colluvium at the base of slopes and in swales, as alluvium on flood plains and in channels, and as lacustrine deposits in natural or artificial lakes usually results in variation in the yield rate for different parts of a watershed.

Field determination of sediment yield may require long-term sampling and measuring procedures. A short-term procedure is to extrapolate (and adjust as appropriate) known sediment yield from measured similar watershed in the same physiographic section.

General

Sources of sediment must be delineated to plan an adequate program for reducing downstream sediment yield. Sediment sources include agricultural land, range and forest land, road banks and ditches, stream channels and banks, flood plains, spoil banks, and gullies. In planning a program to reduce sediment yield, the relative importance of the various sources and the methods for treating them must be determined before the physical and economic feasibility of the program can be determined. Sediment derived from sheet erosion can usually be reduced by land treatment measures, whereas that derived from channel-type erosion usually requires structural works.

A sediment source study is made to determine: (1) the origin of the sediment; (2) the rate of erosion from each source; (3) the proportion of the sediment derived from each source; (4) for program planning or structure design, the kinds of treatment that should be recommended for reducing sediment yield; and (5) the relative effect that reducing erosion from the various sources will have on reducing sediment yield and damage.

The relative importance of the sediment source may differ at different locations in a watershed. Therefore, the treatment measures may also vary, depending on the location in the watershed where a reduction in sediment yield is desired.

Determining the Relative Importance of Various Sources

The following items must be considered in the early stages of any study made to determine the location, extent, and relative importance of the sediment sources.

Maps and Aerial Photographs

Careful review of aerial photographs often reveals where erosion is severe and which channels appear to be carrying the heaviest load of sediment. If soil surveys are available, the information on soils, slopes, land use, and erosion conditions recorded on the maps is very helpful. Using all such information as fully as possible saves considerable time in locating the most obvious sources of sediment.

Distinctive Minerals

The presence of distinctive minerals in modern sediment deposits helps in identifying and evaluating sediment sources. Because a watershed may contain contrasting rock formations, the distinctive erosion products of these rock formations may clearly indicate the location of the sediment sources. These distinctive minerals are quartz, micas, iron oxide, feldspar, chert, and calcite; some can be easily identified and traced to their original source. Other watersheds may lack geologic variety and hence may not provide such specific clues to the location of significant erosion.

Colluviation

Another aid in evaluating the sediment sources is the extent and location of colluvial deposition. If a coarse-grained material such as sand or gravel is being actively eroded, it may produce large volumes of sediment, little of which moves very far from the site of erosion. Substantial deposits may form at the foot of the first slope. Fans and valley deposits may form in small tributary valleys or in the next lower valleys downstream.

Procedure

Any procedure requires study of the various types of erosion apparently producing sediment. Sorting the types of erosion according to the treatments that could be recommended to reduce erosion and thus sediment yield will make the effectiveness of the various treatments much easier to evaluate.

Several procedures can be used to determine the relative importance of the various sediment sources. A recommended procedure is to gather information on that part of the sediment yield which can be attributed to each of the various sources. Erosion and the sediment delivery ratio should be estimated above each reach or other point of interest for the drainage area.

The sediment yield at the point of interest must be allocated to the recognized sources. Analyzing the available data, studying the watershed, and considering the sediment delivery ratios and erosion estimates enable the preparation of a table, such as table 6–1, that indicates the relative importance of the sediment sources.

Table 6–1. — Sediment yield from various sources

	Sediment yield from indicated source					
Reach	Sheet erosion	Gullies	Road-banks	Stream-banks	Scour	Total
	Pct.					
1	88	5	2	3	2	100
2	64	28	3	4	1	100
3	36	64				100

General

Sediment yield is the gross (total) erosion minus the sediment deposited en route to the point of concern. Gross erosion is the sum of all the water erosion occurring in the drainage area. It includes sheet and rill erosion plus channel-type erosion (gullies, valley trenches, streambank erosion, etc.). Measurements or estimates of the sediment yield are needed to evaluate sediment damage and its reduction and to determine the sediment storage requirements for proposed structures. The yield of a given area varies with changes over time in precipitation, cover, and land use patterns. For projection into the future, the present sediment yield must be adjusted to allow for expected changes in these factors.

Climatic Factors

The effect of climatic factors such as precipitation, temperature, and wind on sediment yields varies in different parts of the country. Rainfall and runoff are the primary erosion factors throughout the country. Wind erosion is serious in some sections but is not as widespread as water erosion. The erosive power of rainfall depends on its intensity, duration, and frequency. Seasonal distribution of rainfall is of prime importance in cropland areas because of the condition of the cover at the time of erosion-producing rainfall. Prolonged low-intensity rainfalls are less erosive than brief intense storms. Guidance in computing long-term sheet erosion rates is given in Chapter 3.

Watershed Factors

Important watershed factors affecting sediment yield are size of drainage area, topography, channel density, soils, and cover conditions.

Size

In a given physiographic area, the larger the drainage area, the larger the sediment yield, but generally the sediment yield per unit of area (sediment yield rate) decreases as the size of drainage area increases. In mountainous areas, however, the size of the drainage area often makes no difference in the sediment yield rate. Where active channel-type erosion increases downstream as from bank cutting on the mainstream channel, the sediment yield rate may increase as the size of the drainage area increases. The relationship between size of drainage area and the sediment yield rate must therefore be considered carefully.

In a small watershed, sediment is carried shorter distances and areas of high and low sediment production are less likely to counterbalance each other than in a large watershed. There are fewer types of land use or other watershed variables in a small watershed than in a large watershed. In a small watershed the yield rate is higher and varies more than in a large watershed.

In a small watershed in which the land is used according to its capability, both the erosion rate and the sediment yield rate are low. Conversely, a high erosion rate is sharply reflected in a high sediment-yield rate. Larger watersheds tend to have lower average slopes and less efficient sediment transport than smaller watersheds. Size of the drainage area is therefore an important factor in both the total sediment yield and the sediment yield rate.

The relationship between size of drainage area and sediment yield is complicated by many other factors, such as rainfall, plant cover, texture of the sediment, and land use. All these factors must therefore be evaluated in estimating the volume of sediment from an erosion source, the rate of deposition in a proposed reservoir, or the rate of sediment contribution to any downstream location.

Several investigators have illustrated the relationship of watershed size and sediment yield rate with graphs, curves, and charts. Among them are Gottschalk (1948); Brown (1950); Barnes and Maner (1953); Renfro[1]; Roehl[2]; Beer, Farnham, and Heinemann (1966); and Johnson et al. (1974).

Topography

Shape of the land surface is an inherent feature of the physiographic area in which a watershed is located. Many of the problems of soil and water conservation result from the topography of an individual watershed, especially the proportions of uplands, valley slopes, flood plains, or features such as escarpments, canyons, or alluvial fans. Slope is a major factor affecting the rate of onsite erosion, and topography is important in the delivery of upland erosion products to the stream system.

Drainage density, amount of sloping land, and erosion rate are closely related to the stage of erosional development. Youthful areas are characterized by a relatively high proportion of high, nearly flat upland between stream valleys. Youthful watersheds at high elevations may have deep canyons along the principal streams; youthful watersheds consisting of low glacial plains or other flat areas commonly have poorly developed stream courses and relatively low slopes. Watersheds in areas of old topography also have a relatively small amount of sloping land, but most of the uplands are eroded to low elevations and the greatest proportion of land consists of old, broad valley flats. The proportion of sloping land is usually highest in mature areas, where drainage is well developed and either uplands or valley flats are limited. The average gradient and the average sediment yield tend to be higher in mature areas.

Channel Density

The efficiency of a stream system in transporting sediment out of a watershed is affected by the degree of channelization. A watershed with a high channel density (total length of channel per unit area) has the most thorough water runoff and the most rapid and complete transport sediment from the area. Channel density can be measured on aerial photographs with the aid of a stereoscope.

Soil and Cover Conditions

The kinds of soil and cover are important in sediment yield. In general, the more erodible the soil and the sparser the vegetation, the higher the sediment yield. Estimating the average annual sediment yield from a watershed having many kinds of soil and mixed cover is complex and requires a procedure such as use of a soil-loss equation to determine erosion for the various soil-slope-cover combinations in the watershed. Sediment yield tends to be similar in watersheds of similar size, topography, and cover.

Land Use

According to the 1977 SCS National Erosion Inventory, about 28 percent of the 1,500 million acres of non-Federal land in the United States is cropland; 36 percent is grassland, pasture, and

[1] *Renfro, Graham W. Unpublished reports (1952-54) on upper Arkansas, Red River, and other watersheds. USDA, Soil Conservation Service, Ft. Worth, Tex.*

[2] *Roehl, John W. Unpublished study (1957). USDA, Soil Conservation Service, Spartanburg, S.C.*

range; 25 percent is forest; 6 percent is in residential, industrial, transportation, and other urban and built-up areas; and 5 percent is in other uses.

Land use is determined to some extent by the kind of soil. In turn, land use largely determines the type of cover. If a watershed is primarily agricultural and the annual precipitation is more than 20 in., most of the sediment yield usually is from sheet erosion. In most forest and range country and in areas with less than 20 in. of annual precipitation, channel-type erosion usually produces most of the sediment (Brown 1960).

According to the U.S. Department of Agriculture, conversion of forest land to continuous cultivation of row crops increases erosion 100- to 10,000-fold. Plowing grassland for continuous cultivation of row crops increases erosion 20- to 100-fold (Brown 1960). In the United States, cultivated farm fields that annually lose more than 200 tons/acre from water erosion are not uncommon (Gottschalk and Jones 1955, Gottschalk 1965). Small, intensively cultivated watersheds in western Iowa have had annual soil losses as high as 127,000 tons/mi^2 (Gottschalk and Brune 1950).

Because it encompasses such a broad area, agricultural land produces the most sediment, but progress is being made in conserving agricultural soils. Special uses create serious local problems. Examples follow.

Urbanization. — Construction of an industrial park near Baltimore produced at least five times more sediment than was present in the waters immediately upstream (Wolman 1964).

Areas under construction above Lake Barcroft, Va., and Greenbelt Lake, Md., yielded annual peak sediment-yield rates of 25,000 and 5,600 tons/mi^2, respectively (Dawdy 1967).

Strip Mining. — In Kentucky a watershed with 10 percent of its area disturbed by active strip-mining produced 57 times the sediment measured from a similar but undisturbed adjoining watershed (Collier et al. 1964).

Highway Construction. — Sediment yield from an area in Fairfax County, Va., where a highway was being built was 10 times greater than that from cultivated land, 200 times greater than that from grassed areas, and 2,000 times greater than that from forested areas (Vice, Guy, and Ferguson 1969).

Methods of Determination

Depending on the environment and the data available, the average annual sediment yield in a watershed can be determined from: (1) gross erosion and the sediment delivery ratio, (2) measured sediment accumulation, (3) sediment load records, and (4) predictive equations.

Gross Erosion and the Sediment Delivery Ratio

SCS has used this method extensively for many years with success, particularly in humid sections of the country. It is well suited to estimating current sediment yield and predicting the effect of land treatment and land use changes on future sediment yield. The following equation is used to estimate sediment yield:

$$Y = E(DR)$$

where

Y = annual sediment yield (tons/unit area).
E = annual gross erosion (tons/unit area).
DR = sediment delivery ratio (less than 1).

The gross (total) erosion in a drainage area is the sum of all the water erosion taking place. The method of determining the amount of each type of erosion is outlined in Chapter 3 and in other guides. The sediment delivery ratio is estimated from relationships discussed later in this chapter. Sediment yield is the product of gross erosion and the sediment delivery ratio.

Measured Sediment Accumulation

The measured sediment accumulation in reservoirs of known age and history is an excellent source of data for establishing sediment yield, but deposition in reservoirs and sediment yield are not synonymous. For sediment yield, the amount of accumulated sediment must be divided by the trap efficiency of the reservoir. The amount of sediment that has passed through the reservoir plus the amount deposited in the reservoir equals the sediment yield.

The sediment yield of a watershed can be estimated from measured sediment yield from another watershed in the same major land resource area if the topography, soils, and land use of the two watersheds are similar. For direct extrapolation of sediment yield data, the size of the drainage area of the surveyed reservoir should be no less than one-half nor more than twice that of the watershed under consideration. Beyond these limits the annual sediment yield can be adjusted on the basis of the ratio of the drainage areas to the 0.8 power:

$$Y_e = Y_m \left(\frac{A_e}{A_m}\right)^{0.8}$$

where

Y_e = sediment yield of unmeasured watershed in tons per year.
Y_m = sediment yield of measured watershed in tons per year (measured annual sediment deposition divided by trap efficiency of surveyed reservoir).
A_e = drainage area of unmeasured watershed.
A_m = drainage area of measured watershed.

This relationship must be used with judgment and be confined generally to the humid areas east of the Rocky Mountains.

The amount of sediment accumulated on fans and flood plains over a known period of time can sometimes be used to estimate sediment yield but generally only to verify yield determined by other methods. The procedures for measuring sediment in reservoirs or in valley deposits are discussed in Chapter 7.

Suspended-Load Records

Suspended sediment can be measured by sampling, and water discharge can be determined by gaging at stream cross sections. Sediment yield can be estimated from these data. Sediment concentration in milligrams per liter or parts per million is converted to tons per day by multiplying the average concentration by the volume of water discharged on the day of record and a conversion factor (usually 0.0027). Tons of sediment per day plotted against water discharge in cubic feet per second is a sediment rating curve. The data plotted on log-log paper often approximate a straight line through at least a major part of the range of discharge (see fig. 6–1).

If discharge and concentration data are available, the average annual sediment yield can be estimated by using a flow-duration curve or equivalent tabulations (Anderson 1954). Usually the length of time required to collect a range of suspended-load data large enough to prepare a sediment rating curve prohibits the establishment of a supended-load station for the small watersheds in SCS programs. If such suspended-load records are available from nearby similar watersheds, however, the sediment yield rate can be derived and transposed in the same manner as reservoir sedimentation-survey data (pp. 6–5 and 6–6). The bedload portion of the sediment load is not measured in this method; it must be estimated. It can range from practically none to 50 percent or more of the total load.

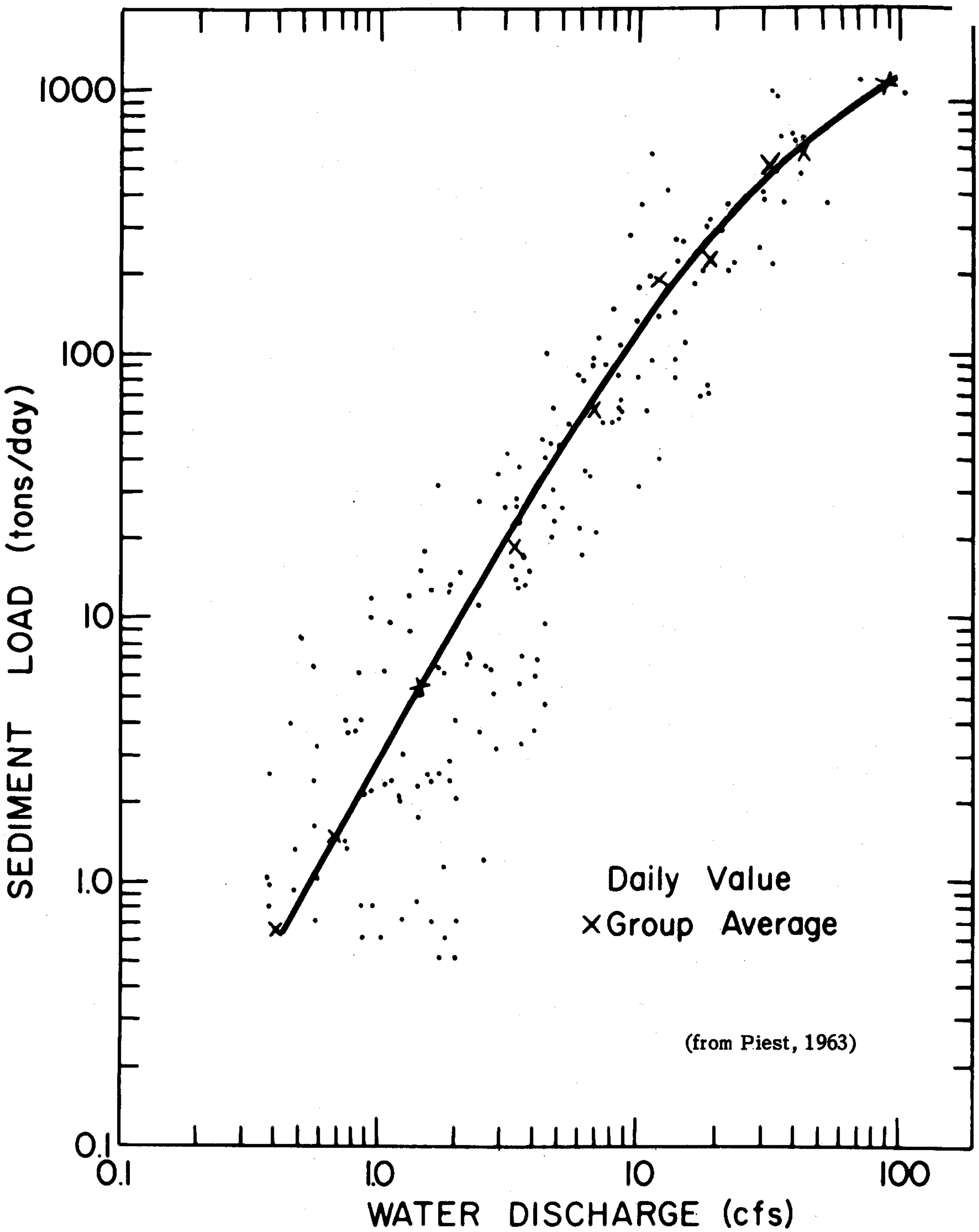
Predictive Equations

Predictive equations based on watershed characteristics have been developed in some areas to estimate sediment yield. These equations express sediment yield as a function of a combination of several measurable independent variables. The variables include size of the drainage area, annual runoff, watershed shape, relief-length ratio, average slope, an expression of the particle size of the surface soil, and others.

Such equations are not numerous but, where developed, they can be used with the understanding that they apply only to the specific area they represent (see Chap. 8).

Information Sources

Information on reservoir sedimentation surveys can be obtained from SCS reports and reports of other federal, state, and private agencies. Suspended-load data for a wide range of watershed sizes, geographic areas, and streamflow quantities are available from water-supply papers and special reports of the U. S. Geological Survey. Many project reports of the Bureau of Reclamation and U. S. Army Corps of Engineers contain sediment yield data for particular drainage basins. Reports of the Inter-Agency Committee on Water Resources should be consulted, as well as river basin reports such as those for the Missouri River and the Arkansas-White-Red Rivers. The Subcommittee on Sedimentation, Inter-Agency Advisory Committee on Water Data, periodically issues summaries of existing sedimentation surveys (Agricultural Research Service 1978) and inventories of sediment-load measurements in the United States (U. S. Geological Survey 1978). Copies of these are available through the committee's SCS representative. United Nations flood-control series bulletins



Direct runoff versus sediment discharge, by day, Pigeon Roost Creek Watershed 5, January 1957—December 1960

Figure 6–1.—A sediment rating curve.

contain some sediment-yield data. Sediment yield to bottom lands, fans, bays, deltas, and other features is evaluated in many of these reports. Sediment yield information is sometimes published in scientific and engineering journals (Gottschalk 1965, Holeman 1968, and Diseker and Richardson 1962), manuals (American Society of Civil Engineers 1975), or conference proceedings (Water Resources Council Sedimentation Committee 1976).

Determining the sediment delivery ratio is of primary importance to geologists if they are to make realistic estimates of sediment yield on the basis of computed gross erosion. No characteristic relationship is known to exist between sediment yield and erosion alone. Many factors influence the sediment delivery ratio and, because these are not uniform from watershed to watershed, the relationship between sediment yield and erosion varies considerably.

Influencing Factors

Each of the following factors can influence the sediment delivery ratio. There may be additional factors not yet identified.

Sediment Source

The sediment source affects the sediment delivery ratio. Sediment produced by channel-type erosion is immediately available to the transport system. Much of it remains in motion as suspended sediment or bedload. Materials derived from sheet erosion, however, often move only a short distance and may lodge in areas remote from the transport system. These materials may remain in the fields in which they originated or may be deposited as colluvium on more level slopes.

Proximity of Sediment Sources

Another factor that affects the sediment delivery ratio is the proximity of the source to streamflow. For example, although a large amount of material may be produced by severe erosion in an area remote from a stream, the delivery ratio and sediment yield may be less than those from a smaller amount of material produced by moderate erosion close to that stream.

Transport System

Runoff resulting from rainfall and snowmelt is the chief transport agent for eroded material. The ability to transport sediment depends on the velocity and volume of water discharge as well as on the amount and character of the material supplied to it. If the amount of sediment in transit exceeds the transport capacity of the system, sediment is deposited and the sediment delivery ratio is decreased. The frequency and duration of discharges affect the total volume of sediment delivered. The extent and condition of the transport system have considerable bearing on the amount of sediment the system can transport. A transport system with high channel density has the greatest chance of acquiring materials from the uplands and should have a high sediment-delivery ratio. The condition of the channels (clogged or open, meandering or straight) affects velocity and, consequently, transport capacity. A high-gradient stream, usually associated with steep slopes and high relief, transports eroded material efficiently. The converse is true of a low-gradient stream.

Texture of Eroded Material

The texture of the eroded material also affects the sediment delivery ratio. Transport of sand requires a relatively high velocity. Much of the sand is deposited in upstream areas wherever velocity drops significantly. Sand usually becomes part of the sediment load only if its source areas are adjacent to an efficient transport system. Eroded silt and clay are likely to stay in suspension as long as the water is moving, and most of such material is delivered downstream. Some of the coarser particles may be deposited as colluvium before they reach the transport system. The sands and larger grain-size materials are usually produced by channel erosion, and the silts and clays are common products of sheet erosion.

Depositional Area

Some sediment is deposited at the foot of upland slopes, along the edges of valleys, in valley flats, in and along main stream channels, and at the heads of and in reservoirs, lakes, and ponds. Such deposition within a watershed decreases the amount of sediment delivered to points downstream.

Watershed Characteristics

The topography of a watershed affects the sediment delivery ratio. Slope is a major factor affecting the rate of erosion. High relief often indicates both a high erosion rate and a high sediment-delivery ratio. The relief/length ratio (R/L ratio) often corresponds closely to the sediment delivery ratio. For use in the R/L ratio, relief (measured in feet) is defined as the difference between the average elevation of the watershed divide at the headwaters of the main-stem drainage and the elevation of the streambed at the point of sediment yield. Length is defined as the maximum valley length (in feet) parallel to the main-stem drainage from the point of sediment yield to the watershed divide. The shape of a watershed can affect the sediment delivery ratio. Channel density also affects the sediment delivery ratio; channel density and topography are closely related. The size of the drainage area is also important. Size can be considered a composite variable that incorporates and averages out the individual effects of variability in topography, geology, and climate.

Procedures for Estimating the Sediment Delivery Ratio

Determining the sediment delivery ratio requires knowledge of the sediment yield at a given point in a watershed and the total amount of erosion. If this information is available, determining the sediment delivery ratio is simple. Values for both these required items, however, usually are not available for most small watersheds.

Gross erosion in a watershed can be estimated by using standard SCS procedures (see Chap. 3). Sediment yield can be determinied from reservoir sedimentation surveys or sediment-load measurements.

Many reservoirs are not located at points where measurements of sediment yield are needed, and a program of sediment-load sampling may be long and expensive. But if the ratio of known sediment yield and erosion within a homogeneous area can be analyzed in conjunction with some measurable influencing factor, these data can be used to predict or estimate the sediment delivery ratio for similar areas where measurements are lacking.

In a given physiographic area, finding measurable factors that can be definitely related to the sediment delivery ratio is the goal of any delivery-ratio analysis. As already pointed out, many factors can affect the sediment delivery ratio. Some are more pronounced in their effect than others; some lend themselves to quantitative expression and others do not.

Statistical analysis is an effective means of developing information for estimating the sediment delivery ratio. The sediment delivery ratio is used as a dependent variable and the measurable watershed factors are used as the independent or controlling variables. For such an analysis, quantitative data on sediment yield, erosion, and measurable watershed factors must be available. Reservoir sedimentation surveys are a source of sediment yield data. Either maps or field surveys can be used to obtain the erosion information and determine the watershed factors. These data can be analyzed to develop a means for estimating the sediment delivery ratio for similar areas. Analyses of this type should be made in consultation with the geologist (sedimentation) of the appropriate national technical center (NTC).

Size of Drainage Area

Data obtained from past studies (Gottschalk and Brune 1950, Woodburn and Roehl[3], Maner and Barnes 1953, Glymph 1954, Maner 1957, Roehl 1962) are plotted in figure 6–2. The figure indicates a wide variation in the sediment delivery ratio for any given size of drainage area. The shaded area represents the range of data and the dashed line is the median. This analysis of data from widely scattered areas does show, however, that there is evidently some similarity in sediment delivery ratios throughout the country and that they vary inversely as the 0.2 power of the size of the drainage area. Rough estimates of the sediment delivery ratio can be made from figure 6–2, but any such estimate should be tempered with judgment, and other factors such as texture, relief, type of erosion, sediment transport system, and areas of deposition within the drainage area should be considered. For example, if the texture of the upland soils is mostly silt or clay, the sediment delivery ratio will be higher than if the texture is sand.

Somewhat more refined relationships between sediment delivery ratio and drainage area have been developed by regions at some NTC's and can be used in place of figure 6–2.

Relief-Length Ratio

The watershed relief-length ratio (Maner and Barnes 1953, Roehl 1962) is a significant indicator of the sediment delivery ratio. Empirical equations were derived to estimate the R/L ratio for the Red Hills of Texas, Oklahoma, and Kansas and for the southern Piedmont region of the Southeast. The significance of the R/L ratio may be less pronounced in some areas than in others, but it is related to, and seems to be a reasonable expression of, several watershed factors.

Source-Texture Analysis

In all the preceding discussion of methods of estimating the sediment delivery ratio, the delivery ratio is a percentage of total erosion. In many places the individual delivery ratio of the component parts of the total erosion is of concern to SCS geologists. Reasonable and realistic values for the delivery of component parts must be estimated from scanty data. One method of obtaining these estimates is to make certain determinations or assumptions about the source of various components of a known sediment yield.

In the following example the method of source-texture analysis is applied to a watershed in which the sediment sources are sheet erosion, gullies, roadbanks, ditches, and receding streambanks. The suspended-sediment yield (determined by sampling) consists of silt and clay, and the bedload (estimated as a percentage of the suspended-sediment yield) is sand. The streambed is in equilibrium and therefore is not considered a net source of sediment under existing conditions. Because of the texture of the sediment and the texture of the material available in the various sources, assume that all the sand is provided by gullies, roadbanks, and ditches and that the fine materials are provided by the receding streambanks and sheet erosion. Assume that 100 percent of the streambank material will be delivered to the point of measurement.

Use the following procedure to determine the sediment delivery ratio:

1. Compute the amount of sediment produced by each source or type of erosion in tons per year.
2. Determine the suspended-sediment yield of the watershed by sampling.
3. Establish a delivery ratio for the gullies and roadside erosion by comparing the amount of sand being carried past the point of measurement with the volume of material provided by gullies, roadbanks, and ditches.

Table 6–2 illustrates source-texture analysis for estimating sediment delivery ratios.

This procedure can be used to estimate the sediment delivery ratio in similar areas. Many broad assumptions are required in an analysis of this

[3]Woodburn, Russell, and J. W. Roehl. Unpublished study (1951). USDA, Agricultural Research Service, Oxford, Miss.

type, and the results will be only as good as the assumptions.

Source Deposition

Another method of determining the sediment delivery ratio is to make a field study of a watershed and estimate the amount of deposition that can be traced to any one source. The difference in the volume of such deposition and the volume of sediment produced by the source gives an estimate of the delivery ratio from that source.

Table 6–2.—Sediment source and the delivery ratio

Sediment source	Erosion[1]		Sediment yield[2]		Delivery ratio
	Sand	Fines	Sand	Fines	
	tons/yr	*tons/yr*	*tons/yr*	*tons/yr*	*Pct.*
Sheet erosion	—	900,000	—	[3]300,000	33
Channel erosion					
Gullies	350,000	—	280,000	—	[4]80
Roadbanks	150,000	—	120,000	—	[4]80
Streambanks	—	900,000	—	900,000	100
Total	500,000	1,800,000	[5]400,000	[6]1,200,000	70

[1]Determine by standard SCS procedures.
[2]Assume that all fines are from sheet erosion and streambanks and all sand is from gullies and roadbanks.
[3]Difference between total yield of fines and yield of fines from streambanks.
[4]Compute as ratio of total sand yield to total sand available; assume equal delivery ratio for gullies and roadbanks.
[5]Estimate bedload as a percentage of the suspended load.
[6]Determine from suspended-load measurements.

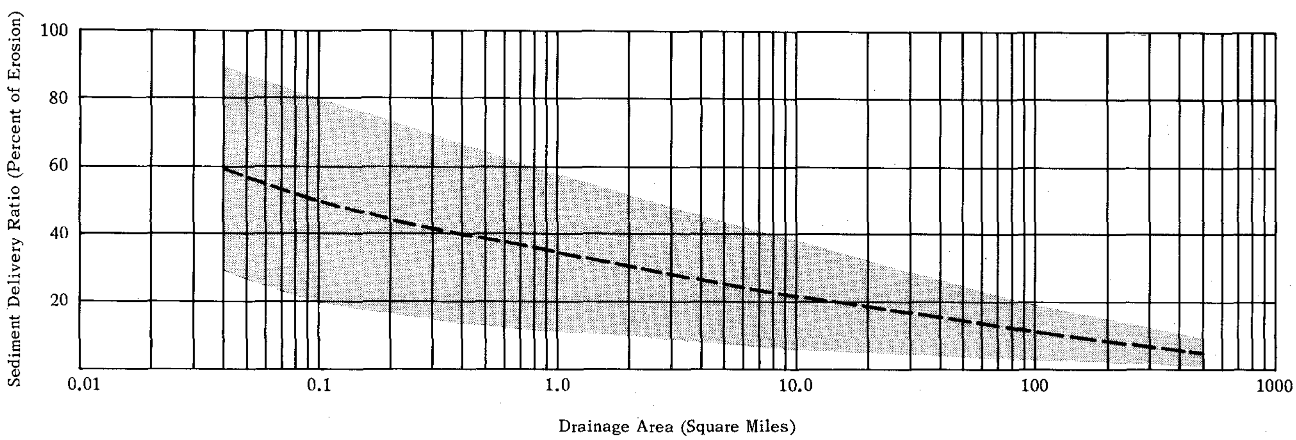


Figure 6–2.—Relationship between drainage area and sediment delivery ratio.

In many places data needed for detailed analyses are insufficient or nonexistent. Using an equation to obtain sediment data outside the physiographic area for which the equation was developed is generally not recommended. Yet SCS geologists must know the sediment delivery ratio to determine the sediment yield and the relative importance of various sediment sources and to recommend measures for reducing the sediment yield.

Information about the sediment yield from some watersheds is available in most areas of the Nation. These data can be obtained from suspended-load records and reservoir sedimentation-survey records. Comparing sediment yield with the calculated gross erosion indicates the expected sediment delivery ratio for an area. This kind of analysis is much broader than a detailed study, and extrapolating such an estimate to other areas can cause error.

References

Agricultural Research Service, U. S. Department of Agriculture. 1975. Present and prospective technology for predicting sediment yields and sources. ARS–S–40, 285 p.

Agricultural Research Service, U. S. Department of Agriculture. 1978. Sediment deposition in U.S. reservoirs: Summary of data reported through 1975. Misc. Publ. 1362.

American Society of Civil Engineers. 1975. Sedimentation engineering. Vito A. Vanoni, ed. Manuals and Reports on Engineering Practice No. 54, Am. Soc. Civ. Eng., New York, 745 p.

Anderson, H. W. 1954. Suspended sediment discharge as related to stream flow, topography, soil, and land use. Am. Geophys. Union Trans. 35(2):268–281.

Barnes, L. H., and S. B. Maner. 1953. A method for estimating the rate of soil loss by sheet erosion from individual fields or farms under various types of land treatment. USDA Soil Conserv. Serv., Western Gulf Region, Ft. Worth, Tex., 12 p.

Beer, C. E., C. W. Farnham, and H. G. Heinemann. 1966. Evaluating sedimentation prediction techniques in western Iowa. Am. Soc. Agric. Eng. Trans. 9(6):826–831.

Boyce, Robert C. 1975. Sediment routing with sediment delivery ratios. *In* Present and prospective technology for predicting sediment yields and sources. USDA Agric. Res. Serv. Publ. S–40.

Brown, Carl B. 1950. Effects of soil conservation. *In* Applied sedimentation, ch. 22, p. 380–406. Parker D. Trask, ed. John Wiley & Sons, Inc., New York.

Brown, Carl B. 1960. Effects of land use and treatment on pollution. Natl. Conf. on Water Pollut. Proc., Public Health Serv., Dep. Health, Educ., and Welfare, p. 209–218.

Collier, C. R., et al. 1964. Influences of strip mining on the hydrologic environment of parts of Beaver Creek Basin, Kentucky, 1955–59. U. S. Geol. Surv. Prof. Pap. 427–B, 85 p.

Costa, John E. 1975. Effects of agriculture on erosion and sedimentation in the Piedmont Province, Maryland. Geol. Soc. Am. Bull. 86:1,281–1,286.

Dawdy, D. R. 1967. Knowledge of sedimentation in urban environments. Proc. Am. Soc. Civ. Eng., J. Hydraul. Div. 93(HY6):235–245.

Diseker, E. G., and E. C. Richardson. 1962. Erosion rates and control methods on highway cuts. Am. Soc. Agric. Eng. Trans. 5(2):153–155.

Glymph, Louis M., Jr. 1954. Studies of sediment yields from watersheds. Int. Union of Geod. and Geophys., Int. Assoc. Hydrol. 10th Gen. Assem., Rome, Italy, Part 1, p. 178–191.

Gottschalk, L. C. 1948. Analysis and use of reservoir sedimentation data. Fed. Inter-Agency Sediment. Conf. Proc., Denver, Colo., p. 131–138.

Gottschalk, L. C. 1965. Sedimentation transportation mechanics: Nature of sedimentation problems. Proc. Am. Soc. Civ. Eng., J. Hydraul. Div. 91(HY2):251–266.

Gottschalk, L. C., and G. M. Brune. 1950. Sediment-design criteria for the Missouri Basin loess hills. USDA Soil Conserv. Serv. Tech. Publ. 97.

Gottschalk, L. C., and V. H. Jones. 1955. Valleys and hills, erosion and sedimentation. *In* Water, p. 135–143. U. S. Dep. Agric. Yearb. Agric.

Holeman, John N. 1968. The sediment yield of major rivers of the world. Water Resour. Res. 4(4):737–747.

Interagency Advisory Committee on Water Data, Subcommittee on Sedimentation. 1980. Notes on sedimentation activities, calendar year 1979. Office of Water Data Coordination, U. S. Geol. Surv., Reston, Va.

Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation. 1962. Inventory of published and unpublished sediment-load data, U. S. and Puerto Rico, 1950–60. U. S. Geol. Surv. Water-Supply Pap. 1547, 117 p.

Johnson, C. W., G. R. Stephenson, C. L. Hanson, R. L. Engleman, and C. D. Engelbert. 1974. Sediment yield from southwest Idaho rangeland watersheds. Am. Soc. Agric. Eng. Pap. 74–25205.

Maner, Sam B. 1957. Factors affecting sediment delivery rates in the Red Hills physiographic area. Am. Geophys. Union Trans. 39:669–675.

Maner, Sam B., and L. H. Barnes. 1953. Suggested criteria for estimating gross sheet erosion and sediment delivery rates for the Blackland Prairies problem area in soil conservation. USDA Soil Conserv. Serv., Ft. Worth, Tex., 17 p.

Piest, R. F. 1965. The role of the large storm as a sediment contributor. *In* Proc. 1963 Fed. Inter-Agency Sediment. Conf., Jackson, Miss., U. S. Dep. Agric. Misc. Publ. 970, p. 98–100.

Roehl, John W. 1962. Sediment source areas, delivery ratios, and influencing morphological factors. Presented at IAHS Symposium on Land Resources, Oct. 1962. Int. Assoc. Hydrol. Sci. Publ. 59.

U. S. Geological Survey, U. S. Department of the Interior. 1978. Index to water-data acquisition. Office of Water Data Coordination, Reston, Va.

Vice, R. B., H. P. Guy, and G. E. Ferguson. 1969. Sediment movement in an area of suburban highway construction, Scott Run Basin, Fairfax Co., Virginia, 1961–64. U. S. Geol. Surv. Water-Supply Pap. 1591–E. 41 p.

Water Resources Council Sedimentation Committee. 1948. Proc. 1st Fed. Inter-Agency Sediment. Conf. PB 245–379. Natl. Tech. Inf. Serv., Springfield, Va., 314 p.

Water Resources Council Sedimentation Committee. 1963. Proc. 2nd Fed. Inter-Agency Sediment. Conf. PB 245–380. Natl. Tech. Inf. Serv., Springfield, Va., 933 p.

Water Resources Council Sedimentation Committee. 1967. Proc. 3rd Fed. Inter-Agency Sediment. Conf. PB 245–100. Natl. Tech. Inf. Serv., Springfield, Va., 802 p.

Wolman, M. G. 1964. Problems posed by sediment derived from construction activities in Maryland. Md. Water Pollut. Control Comm. Rep., 125 p.

United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Chapter 7

Field Investigations and Surveys

Contents

	Page
General	7-1
Reservoir sedimentation surveys	7-1
Purpose	7-1
General plan	7-2
Safety measures	7-2
Selecting reservoirs	7-3
Scheduling	7-3
Equipment	7-4
Boat and associated equipment	7-4
Range-cable equipment	7-5
Sounding equipment	7-6
Equipment for measuring thickness of sediment	7-7
Equipment for determining specific weight of sediment	7-9
Survey methods	7-10
Range survey	7-11
Contour survey	7-14
Contour-range survey	7-14
Measuring thickness of sediment	7-14
Sampling for volume-weight of sediment	7-15
Direct measurement of volume-weight	7-16
Notekeeping	7-16
Recording measurements	7-16
Sediment samples	7-18
Fathometers	7-18
Computing water capacity and sediment volume	7-18
Range method	7-19
Contour method	7-24
Contour-range method	7-25
Land surveys	7-25
Survey reports	7-27
Outline	7-30
Record maintenance	7-31
Flood-plain damage surveys	7-31
Purpose and objectives	7-31
Preliminary sedimentation investigations	7-31
Detailed sedimentation investigations	7-32
Developing the plan	7-32
Boring and logging	7-32
Interpreting test-hole data	7-32
Survey methods	7-33
Mapping method	7-33
Range method	7-34
Deposition and scour damages	7-39
Equilibrium damages	7-39
Increasing damages	7-39
Decreasing damages	7-39
Channel erosion damages	7-39
Swamping damages	7-40
References	7-43

Figures

Page

7–1. Reel without brake for range cable 7-5
7–2. Reservoir-surveying equipment 7-6
7–3. Color-code markings for sounding lines 7-7
7–4. Bell-shaped sounding weight 7-8
7–5. Fathometer showing recorded depths of range cross section 7-9
7–6. Sediment-sampling spud and carrying case 7-9
7–7. Piston-type sediment-sampling tube 7-10
7–8. Sediment density probe 7-10
7–9. Example of range layout 7-12
7–10. Notes from the measurement of a range 7-17
7–11. Notes for sediment sample 7-18
7–12. Computation sheet for determining range area 7-19
7–13. Instructions for computing reservoir—range method 7-21
7–14. Computing reservoir capacity—range method 7-22
7–15. Methods of determining "h" values 7-23
7–16. Reservoir capacity—contour method 7-26
7–17. Stage-area curve 7-27
7–18. Reservoir sediment-data summary 7-28
7–19. Flood-plain damage survey 7-35

Tables

Page

7–1. Flood-plain damage and estimated recovery period related to depth and texture of sediment deposit 7-33
7–2. Type and extent of physical land damage 7-36
7–3. Summary of flood-plain damage, Reach B 7-36
7–4. Sample worksheet for range data summary 7-36
7–5. Computation of the weighted averages of types of damage, Reach A 7-37
7–6. Reach damage summary from range data 7-38
7–7. Summary of flood-plain damage, Reach A 7-41

Chapter 7 Field Investigations and Surveys

General

Soil Conservation Service geologists are responsible for making field investigations and surveys concerning sedimentation, especially the effect of sediment accumulation on SCS projects and, conversely, the effect SCS projects can be expected to have in reducing sediment yields. The procedures and techniques necessary for carrying out these investigations have been developed by SCS. They can be learned through on-the-job training or through workshops, formal training sessions, and study of technical releases and handbooks. This chapter is intended to provide guidance in surveying sediment deposition in reservoirs and on flood plains.

The field work associated with obtaining information on sheet and channel erosion is described in Chapter 3, Erosion.

The measurement of suspended-sediment loads is not a primary function of SCS. Such data have been collected by several federal agencies and others. One source is the Index to Water-Data Acquisition (U.S. Geological Survey 1979).

Reservoir Sedimentation Surveys

Procedures for measuring the volume of sediment in a reservoir were established by SCS in 1935 in connection with a nationwide study of reservoir sedimentation (Eakin 1939). Many of these procedures, with some modifications, are still used by SCS and other federal and state agencies. Since SCS is mainly concerned with small watersheds, the discussion of methods, procedures, and equipment in this chapter is limited to those that can be adapted to relatively small reservoirs.

Purpose

The primary purpose of a reservoir sedimentation survey is to determine the volume and weight of sediment accumulated between surveys or during the recorded period of storage. This information may be needed to:

1. Estimate sediment yield for given watersheds or land resource areas.
2. Evaluate sediment damage.
3. Provide basic data for planning and designing reservoirs.
4. Evaluate the effects of watershed protection measures.

5. Determine the distribution of sediment in a particular reservoir.
6. Predict a reservoir's life expectancy or period of useful operation.

General Plan

The fieldwork needed depends on the choice of surveying methods and may include aerial and topographic mapping, locating ranges, sounding and leveling range cross sections, and directly measuring and sampling sediment deposits.

Office work includes preparing a reservoir map, computing the area of cross sections, measuring the surface area of segments, and computing the original capacity and sediment volume.[1] Additional information can be obtained from topographic maps and aerial photos; examples include measurements of the total drainage area and the net sediment-contributing area, determination of the type and area of various land uses, and data for computing erosion. Preparing a reservoir sediment summary sheet and occasionally a formal report completes the office work.

The volume of sediment in a reservoir can be determined by directly measuring the volume of sediment deposits or by determining the reservoir's present capacity and subtracting this from its original capacity.

For the best results from the second method, an accurate map of the original reservoir basin is essential. If such a map is not available, one must be constructed. A map made about the time the dam is closed is desirable, but such maps usually are not available for the smaller and older reservoirs. Any error in determining the original capacity will cause a corresponding error in the computed volume of sediment. Even though the difference between the estimated original capacity and the true original capacity may be relatively small in terms of total capacity, this difference could cause a considerable error in the estimated volume of sediment in a reservoir if that volume is small in comparison with the total original capacity.

If a map of the original reservoir basin is not available or if there is doubt about its accuracy, the volume of sediment deposits and the present storage capacity should be measured directly. The sum of these two volumes below crest elevation is the reservoir's original storage capacity.

[1]*The procedures are explained on pages 41 to 53. Computer programs are available to reduce the amount of manual computation.*

Safety Measures

All safety regulations and practices prescribed in SCS safety handbooks and guides must be followed.

In any work done on or around water, precautions must be taken against drowning. Every employee working from a boat must be able to pass a standard Red Cross swimming test, and all boat occupants must wear life preservers. The cushion-type preserver provides comfort in the boat but is suitable only as a supplement to the vest-jacket preserver, which has been approved by the Coast Guard as being the safest type of preserver. It is effective even if a person becomes unconscious, but some models are cumbersome and hot. An improved inflatable type is being used on SCS surveys. For recommendations and details on these vest-jacket preservers, contact the Safety Officer, SCS, P.O. Box 2890, Washington, D.C. 20013.

State boating laws range from general safety requirements to requiring a state permit to own or operate a boat. Reservoir-surveying parties must know and observe all state boating laws.

Releasing the tension on the range cable is a potentially dangerous step in the range survey procedures. The ratchet of the reel must be unlocked before the cable is rewound after all the measurements have been made. Be careful in releasing the tension because the crank handle can spin and break any bones in its path.

Wear gloves when handling the range cable to prevent injury from small steel slivers of broken cable strands. Cost, delay, and danger can result if a cable is snagged on a lake-bottom obstruction or becomes snarled in the propeller of the outboard motor. Floats to support the cable help reduce these problems. A cable stretched across a range line may be under considerable tension. Personnel near the reel or near the opposite end of the cable should remain well to the side of the cable and never be directly in line with or behind the cable fastening. Backlash from a cable that suddenly gives way can cause serious injury.

Lines for sounding and sediment sampling are other sources of accidents. They should be free to run out without entanglement when spuds are thrown over the side or when sampling equipment is lowered. Keep the lines in good condition and attached securely. Replace frayed lines before a parted line can cause loss of equipment and create additional hazards during attempts to recover the lost equipment. If range lines are used on lakes with boat traffic, clearly flag the lines to warn other boats to stay clear.

It is impractical to list all the boating practices that may be dangerous. Obeying the following rules should ensure safety:

1. Do not use boats that are less than 14 ft long, easily capsized, or in danger of sinking.
2. Do not overload boats.
3. Do not use a motor too large for the boat.
4. Go ashore during storms.
5. In general, use common sense in making surveys on and around water.

In some northern states, reservoir sedimentation surveys are made during the winter through ice. Such surveys should be undertaken only after determining that the ice is thick enough to support the personnel and equipment to be used. The following general guidelines were developed by the Snow, Ice, and Permafrost Research Establishment (SIPRE), U.S. Army Corps of Engineers, for moving weights on clear, sound, fresh-water ice:

Load	Ice thickness
One person on foot	2 in.
Passenger car, 2 tons gross	7-1/2 in.
Light truck, 2-1/2 tons gross	8 in.
Medium truck, 3-1/2 tons gross	10 in.
Heavy truck, 7 to 8 tons gross	12 in.

Slightly thicker ice is required to support parked loads. The first cracking need not cause concern. The bearing capacity of ice is substantially higher than the load that produces the first crack and there is ample warning before the ice fails. Prolonged application of a load, however, produces failure; quick loading or moving the load around reduces the danger. If sagging is noticeable, remove the load.

Use extreme caution after spring melt begins. Survey through ice only in periods of moderation in wintry weather. Windy, stormy, or intensely cold weather is not conducive to safe, accurate surveys.

Special safety precautions must be taken on surveys requiring instruments that contain radioactive elements. Details on equipment and authorization for use may be obtained from the national technical center (NTC) sedimentation geologist.

Selecting Reservoirs

The reservoirs selected depend on the purpose of the survey. The following criteria should be considered when planning reservoir sedimentation surveys to obtain basic data on sediment yield for use in planning or design.

Select reservoirs draining watersheds that are typical of or similar to those in which the proposed structure is to be located. Thus, the watershed of a reservoir to be surveyed should be no more than twice nor less than half the area of the watershed above the proposed structure. Furthermore, the topography and land use should be similar unless suitable detailed soil, slope, and cover data for the watershed are available to allow the yield to be adjusted in accordance with established procedures.

Study the history of the reservoir before starting a field survey to be sure that the date storage began is known; that the dam has not been breached, causing the loss of unknown volumes of sediment; and that the volume of any sediment removed by dredging or other means can be determined with reasonable accuracy. Unless measurements of sediment outflow are available, avoid surveying reservoirs that have a low trap efficiency. Avoid surveying reservoirs with short-term records unless periodic resurveys are planned.

Take advantage of any opportunity to survey a reservoir when it has been drained for purposes such as fish management. Measurements of sediment and present storage capacity are more accurate, and the time required for the survey is less, for a drained than for a full reservoir.

Get permission from the reservoir owners or operators before starting a sedimentation survey.

Scheduling

SCS state staffs may survey and periodically resurvey the sediment accumulation in selected floodwater-retarding and multiple-purpose reservoirs built under SCS supervision. Send a data summary sheet (Form SCS–ENG–34) immediately to the sedimentation geologist of the responsible NTC. The data obtained will expand our knowledge of sedimentation processes, especially the sediment yield, distribution of sediment deposits within reservoirs, and, at times, sediment sources. This information will provide important design criteria and enable more accurate cost estimates of any planned structure. Collection and evaluation of information on the effect of dams on downstream channel reaches and downstream reservoirs are also valuable.

Before starting a survey, often during construction of the dam, establish two permanent bench marks. For convenience, place at least one on the centerline of the dam. To avoid any settling that could affect its elevation, place the bench mark on nonfill material. Before the reservoir is filled, prepare a contour map of the reservoir below the emergency spillway elevation. A geologist familiar with sedimentation survey procedures should locate the ranges to be surveyed as a part of the after-construction survey. The geologist should recognize any topographic irregularities that might influence deposition and the accuracy of subsequent surveys. A contour interval of 2 ft is generally used; use of 1-ft intervals increases the precision of the surveys.

If there is no original contour map of the reservoir, make a survey immediately after the structure starts to function. The date that the principal spillway discharges water is usually considered the beginning of the structure's normal operation. For dry dams, normal operation begins when major construction in the site area is completed.

Resurveys are desirable 5 and 10 years after the initial survey at 10-year intervals thereafter. Additional surveys should be made after major storms. For this purpose, a major storm is considered one in which precipitation equals or exceeds the amount expected from a 10-year-frequency rainfall of 6 hr duration. Data on the amount of precipitation for such a storm anywhere in the United States can be obtained from a hydrologist or from U.S. Weather Bureau (1961, Chart 32).

Equipment

If an accurate sedimentation survey of a reservoir is desired and the reservoir has not been surveyed before, it is necessary to establish engineering control by using standard surveying procedures. Equipment used may include a transit or a plane table and alidade, a stadia rod, a plotting scale, a notebook, a base map or aerial photograph if available, and other materials ordinarily used in engineering surveys. A dry reservoir can be surveyed with this equipment plus a soil auger for measuring sediment thickness and equipment for obtaining undisturbed samples for volume-weight determination. In making surveys through ice, either a hand or power auger or an ice chisel can be used to make holes in the ice. Chain saws can do the job but may be hazardous for those unfamiliar with their operation.

The following additional equipment is needed if part or all of the reservoir basin is submerged:

1. Boat and associated equipment.
2. Range-cable equipment.
3. Sounding equipment.
4. Equipment for measuring thickness of sediment.
5. Equipment for sampling or determining specific weight of sediment.

Boat and Associated Equipment

A 14-ft, flat-bottom, lightweight, shallow-draft boat is most practical for reservoir sedimentation surveys. An outboard motor greatly expedites work for reservoirs of several acres or more. A well in the boat eliminates the need to work over the side. The following are specification guidelines for a satisfactory boat:

1. Length, 14 ft or longer.
2. Center width, 4 ft.
3. Construction, magnesium or aluminum with styrofoam-filled compartments under the seats.
4. Sidewalls, 20 in. high and ribbed for reinforcement against strain.
5. Bottom, flat or shallow "v".
6. Flooring, flat bottom or bottom covered with removable wood grating (sometimes called duckboards).
7. Oarlocks, placed to give maximum rowing efficiency.
8. Transom, constructed of material able to carry an outboard motor.

A two-wheel boat trailer is desirable for transporting a 16-ft or longer boat, although such boats can be transported by truck. Smaller, lightweight boats can be transported satisfactorily by station wagon or on securely anchored car-top racks.

It is efficient to use two boats on some surveys. One boat can be used for moving equipment, running errands, and locating range ends and the other for sounding, spudding, and sampling.

Range-Cable Equipment

For economy, expediency, and accuracy, SCS has long used the range-cable survey method for small reservoirs. This method permits locating soundings on a map or aerial photograph and reduces the size of the crew required for the survey.

The equipment includes a reel, cable, and line meter. The recommended reel holds at least 2,500 ft of 3/32-in.-diameter airplane cable. Secure the cable at each side of the reservoir while sounding the range. A ratchet assembly prevents the reel from unwinding (fig. 7–1). A line meter is used to measure the length of cable passing through the meter. Mount the reel on a short plank or board that can be fastened in the boat or secured on shore at one end of a survey range. Handles mounted on the plank increase safety and convenience when moving the reel and cable. Since this equipment is used in connection with the range type of survey, instructions for its use are included in the discussion of range surveys.

Some of this equipment is not available as standard equipment and must be fabricated. The following notes will help in assembling the parts.

Reel.—Figure 7–1 is a drawing of an aluminum reel developed jointly by the U.S. Army Corps of Engineers and the U.S. Geological Survey. This reel is unavailable with or without a brake. A brake, however, is recommended as a safety feature. The reel is available from U.S. Geological Survey, WRD, Gulf Coast Hydroscience Center, Hydrologic Instrumentation Facility, Bldg. 2101, NSTL Station, MS 39529. The stock number for the reel with brake is 1304001.

A 2-hp, 4-cycle engine and set of belts can be used for rapid rewinding of the cable. This engine reduces both the labor and the time required to wind the cable, but it also reduces the reel's portability.

Cable.—The cable ordinarily used by SCS personnel is galvanized aircraft cable with 3/32-in. outside diameter (O.D.) and 7 × 7 construction; it is available commercially.

A plastic water-ski tow cable of 1/4-in. diameter has been used with good results. It is made of polyethylene fibers and has a tensile strength of 1,100 lb. This lightweight cable, 1 lb/100 ft, floats on the water and can be obtained at most sporting-goods stores. It is a braided rope that does not form loops readily. It breaks if hit by a high-speed boat, but if broken, it can be repaired easily by telescoping one end into the other.

One disadvantage of this plastic cable is that it is deflected by winds. If the ranges are 800 to 900 ft

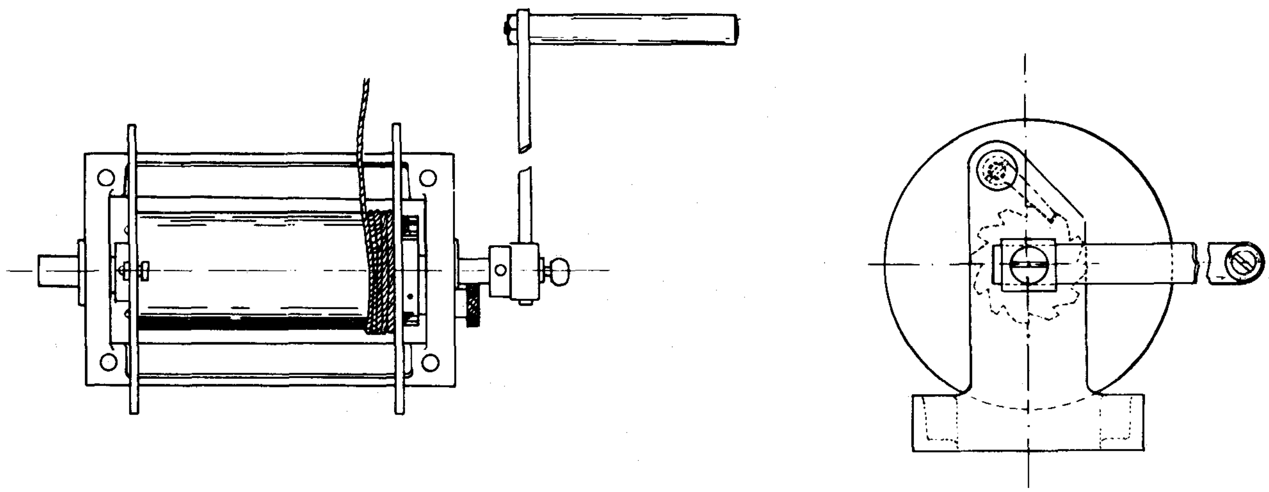


Figure 7–1.—Reel without brake for range cable.

long, consider the velocity and direction of the wind. Run the longer ranges during calm periods or when the wind approximately parallels the range. Ranges as long as 3,300 ft have been run satisfactorily with this plastic cable on very calm days.

A 3/32-in., 7 × 7 steel cable coated with nylon to 1/8-in. O.D. is also available. The coating eliminates the undesirable fraying associated with uncoated steel cable, but it also reduces the length of cable that can be wound on the reel by about 50 percent.

Line meter.—Line meters with hardened steel sheels or wheels coated with urethane are recommended. Several types of open-throat line meters that can easily be detached from the range cable are available, and they have a definite advantage over those that cannot be detached.

Other items.—Sheaves, cable guides, and weed strippers can be fabricated from items available at most hardware stores, mail-order houses, and marine supply companies.

Empty screw-capped gallon tin cans or plastic containers can be used to support the steel cable on long ranges. One float per 200 ft of line is enough to keep the cable afloat. Range cable equipment is shown in figure 7–2.

Two-way radios can be used to expedite surveys.

Sounding Equipment

Any of several types of sounding equipment can be used, depending on conditions. SCS personnel commonly use a sounding line and weight, a sounding pole, or an echo-sounding instrument. Bronze-core rope sounding lines are best suited for use by SCS personnel. If soundings are to be made in deep water, use wire lines for boat-mounted, manually operated reels with registering sheaves. Most reservoirs surveyed are relatively small, with a water depth of 50 ft or less, so hand-line sounding with a rope sounding line is practical; this method is faster and requires less equipment than wire-line sounding. A cotton-covered, bronze-core tiller rope of 1/4-in. diameter is recommended because of its durability and ease in handling (fig. 7–2). Cure the rope sounding lines (soak and dry under tension) before painting them.

Mark rope sounding lines in color at 0.5-ft intervals to identify the 0.5-ft, 1.0-ft, and 5.0-ft markers and each subsequent 10-ft interval marker (fig. 7–3). Water depth can be measured accurately to 0.5 ft and estimated to the nearest 0.1 ft (Gottschalk 1952). Use a high-grade, water-resistant enamel, preferably one of the synthetics that come in a variety of colors. Before painting a new line, remove the waterproof coating from the areas to be painted and outline the marks with masking tape. The single stripes for the 0.5-ft marks should be 0.5 in. wide and all other stripes 1 in. wide. Stripes in a group should be 0.25 in. apart. Use the center of a stripe or group of stripes as the reference point for measuring. Provide enough unpainted line to attach the sounding line to the weight.

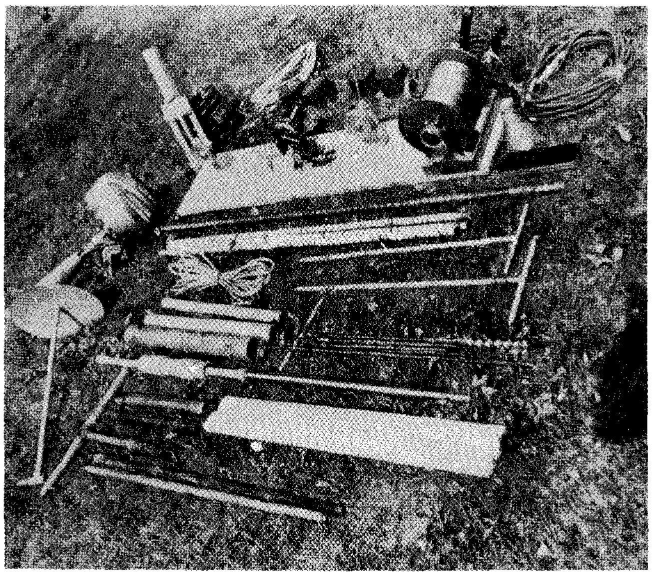


Figure 7–2.—Reservoir-surveying equipment.

Sounding weights are bell-shaped and made of cast aluminum (fig. 7–4). For water less than 100 ft deep, use a 5-lb aluminum weight; for water deeper than 100 ft, a 9-lb weight is best. The 9-lb weight is the same size as a 5-lb aluminum bell but is filled with lead.

Never tie the lines directly to the sounding weight. Use a clevis, snaphook, or oval galvanized metal thimble to protect the lines against wear. If using a clevis, the type with the pin held in place by a cotter key is better insurance against loss of equipment than one with a screw-type pin. Check sounding lines frequently to avoid inaccuracies caused by stretching or shrinking of the line. Discard a line if a constant error of more than 1 percent is observed.

Another device for determining water depth is a sounding pole. Use a sounding pole no more than 30 ft long, because a longer pole is awkward to handle. A sectional thin-wall conduit, 1 in. in diameter, is satisfactory. The sections are 5 ft long and are fastened together with threaded dowels. The pole is lightweight aluminum, and the length can be changed easily by adding or removing sections.

Round plates of various diameters can be fastened to the butt of the pole to aid in identifying sediment surfaces of various softness. These plates can be designed to retract when additional pressure is applied. Sounding poles can also be made of wood. Wood closet rods or windmill pump rods are usually available at local lumberyards and can be made into serviceable sounding rods. The length available usually does not exceed 18 ft, but these poles are lightweight and float if dropped overboard. Mark these sounding poles either by color code or by painting in the numbers.

A fathometer provides a practical and rapid method of measuring water depth. A fathometer is a portable, graphic-recording, echo-sounding instrument designed for measuring depth from a boat (fig. 7–5). It consists of three separate units. The first unit, called the transducer or fish, is attached to the side of the boat and submerged just below the water surface. It emits and receives sonic waves. The time a wave takes to travel to the bottom of the reservoir and return indicates the depth of the water. The recorder, the second unit, is in an aluminum case containing the recording apparatus, paper, amplifier, and phasing and keying circuits. The third unit, an automobile-type battery of appropriate voltage, supplies the necessary power.

One advantage of the fathometer over hand sounding is that it records a continuous cross section of the range instead of a single depth every 20 ft or so. If it is operated from a boat moving at a uniform speed along a range, a constant-scale profile is obtained. When sounding by hand, a thalweg or other depth irregularity can be missed.

Check the calibration of the fathometer from time to time by hand sounding. Although nonrecording depth indicators are available at a fraction of the cost of a fathometer, they are subject to error and are not recommended.

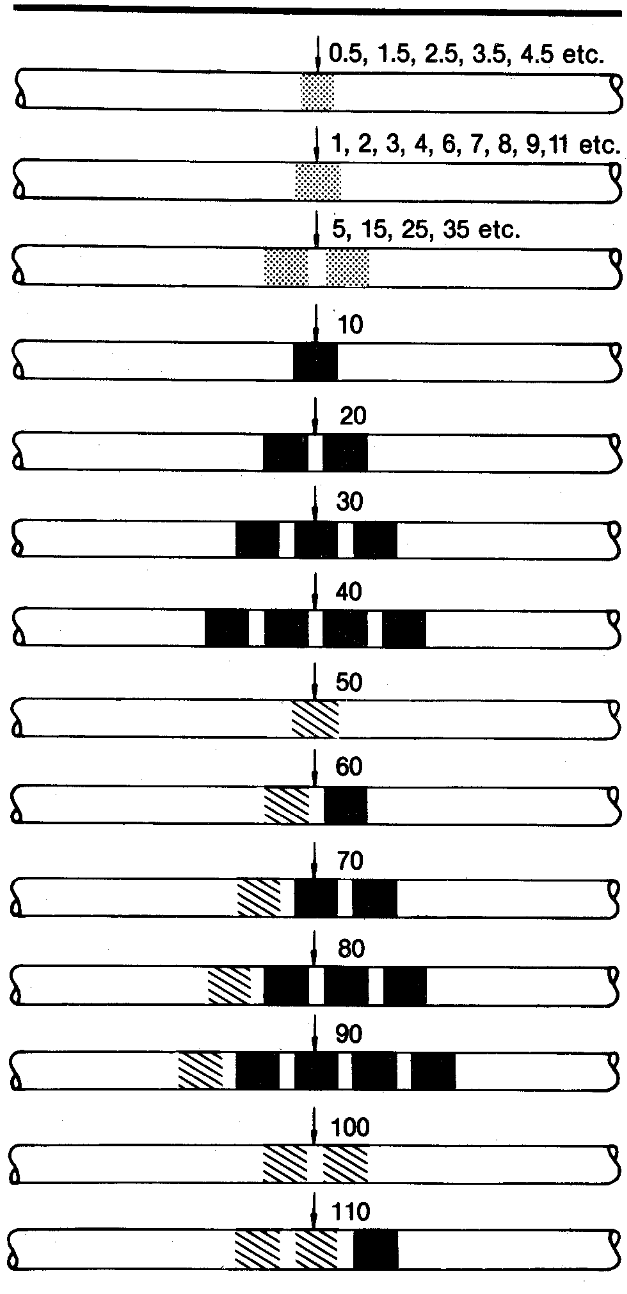


Figure 7–3.—Color-coded markings for sounding lines (in feet).

Equipment for Measuring Thickness of Sediment

If accurate maps of the original reservoir basin are not available, the thickness of accumulated sediment must be measured directly to determine the original capacity and sediment volume. A spud,

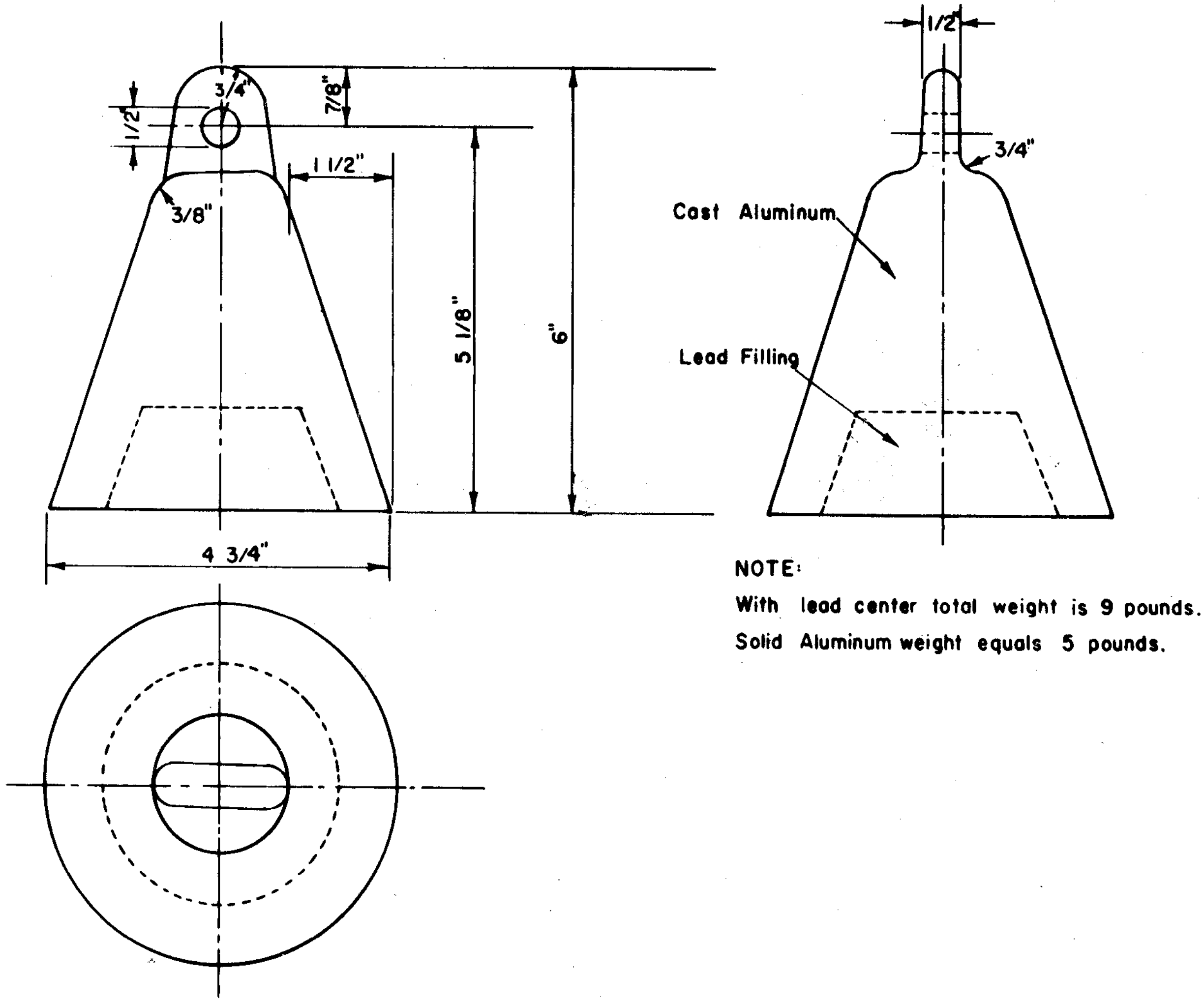


Figure 7–4.—Bell-shaped sounding weight.

sounding pole, or auger can be used for this purpose, depending on local conditions.

A sectional spud of 3-ft sections that can be joined with nickel-steel alloy dowel pins to a length of 18 ft is recommended. If a single continuous spud is fabricated, a 6-ft length is recommended. Longer spuds can be made, but they are difficult to handle and store. A sectional spud can be packed in a carrying case for easy transportation (fig. 7–6). Detailed drawings for the sectional spud are available on request from the Director, Engineering, SCS, P.O. Box 2890, Washington, D.C. 20013.

Spuds are made of case-hardened or tempered steel rods, 1-1/2 in. in diameter, into which encircling triangular grooves are machined at intervals of 0.1 ft. Each groove tapers outward from a maximum depth of 1/4 in. to 0 at the rim of the groove 0.1 ft above. The base of each cone is machined to a depth of 1/8 in., forming a cup to catch and hold the sediment. Four grooves are machined around the circumference of the bottom cone to catch sediment. A single groove is placed on every 10th cone to indicate measurements in feet. The sectional spud is equipped with various types of points for use under different conditions.

Concrete-coated reinforcing steel bars can also be used as spuds. The surface should be rough to facilitate retention of silt; a rusty rod works very well. Spuds are used with a 3/8- or 1/2-in. nylon rope. This rope can be marked, attached, and otherwise treated the same as a sounding line.

A sounding pole or auger also can be used to measure sediment thickness. Sounding poles are best suited to the shallow water areas of reservoirs and the loosely compacted sediments overlying a firm, hard bottom. An auger with a 1-1/2-in. (O.D.) pipe and 5-ft extensions can be used to measure thick compacted sediments and exposed deposits.

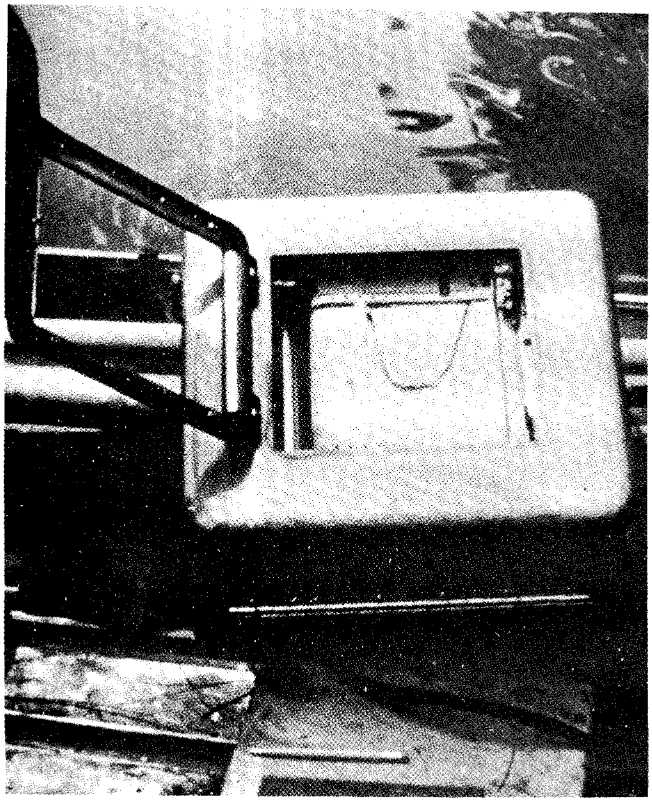


Figure 7–5.—Fathometer showing recorded depths of range cross section.

Equipment for Determining Specific Weight of Sediment

Sampling tube.—Undisturbed samples of exposed deposits can be obtained by forcing a thin-walled cylinder, such as a Shelby tube, into the sediment. Samples of submerged sediment can also be taken with a Shelby tube or similar sampler if surveys are made through ice to support the equipment. For information on such samplers see Chapter 2, Section 8, Engineering Geology, of the SCS National Engineering Handbook.

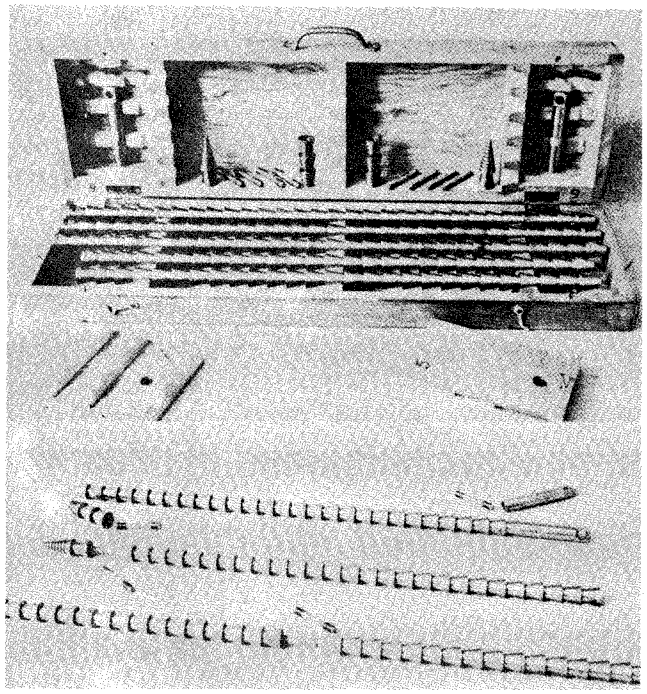


Figure 7–6.—Sediment-sampling spud and carrying case.

A stationary piston-type sampler is needed to obtain samples of submerged sediment. SCS is now using a piston-type sampling tube patterned after one developed by the Division of Water, Ohio Department of Natural Resources, Columbus, Ohio (Gottschalk 1952).

This sampler consists of a brass tube, 1-1/2-in. inside diameter (I.D.), attached to a 3/4-in. standard iron pipe. A standard double-acting water-pump piston attached to a 7/16-in. "sucker" rod is placed in the tube. The sampler is forced into the sediment by a driving weight made of larger diameter pipe that slides on the section of the 3/4-in. pipe. The length of the brass tubes can vary, but a 2- or 3-ft length serves well. Larger diameter tubes can be used.

This sampler is not available as standard equipment from manufacturers, but it can be fabricated in a machine shop. Figure 7–7 shows the dimensions and other information required for fabrication.

A modified piston-type sediment sampler has been developed by SCS in Texas. The I.D. of the brass barrel has been enlarged to contain a plexiglass tube of varying length with 1-3/8-in. I.D. The piston rod has a hole through the center and a needle valve at the top. These modifications permit better recovery of sediment difficult to sample and disturb the sample less. Specifications are available from the Director, Engineering, SCS, P.O. Box 2890, Washington, D.C. 20013.

Stationary piston samplers of larger diameter for use with standard Shelby tubes of 1-7/8-in. and larger I.D. are available from drilling supply companies.

The specific weight of a sediment sample can be determined in the field with equipment such as a carbide moisture meter or an oven and scales.

Density probe.—One probe uses radium–226 as the source of gamma rays. The radioactive source and the detector are separated by a plug and a spacer at each end of the plug. The detector consists of a cluster of three Geiger-Müller tubes. The count is recorded in a nuclear scaler connected by electical cable to the detector in the probe (fig. 7–8).

A sediment density probe formerly owned by SCS has been transferred to the U. S. Army Corps of Engineers. It is available on loan, with an operator, on a reimbursable basis. To borrow, write to the U. S. Army Corps of Engineers, Missouri River Division, Omaha, NE 68101.

The Agricultural Research Service (ARS) has sediment density probes that are sometimes available for loan. ARS has issued several reports on radioactive sediment-density probes (Heinemann 1963).

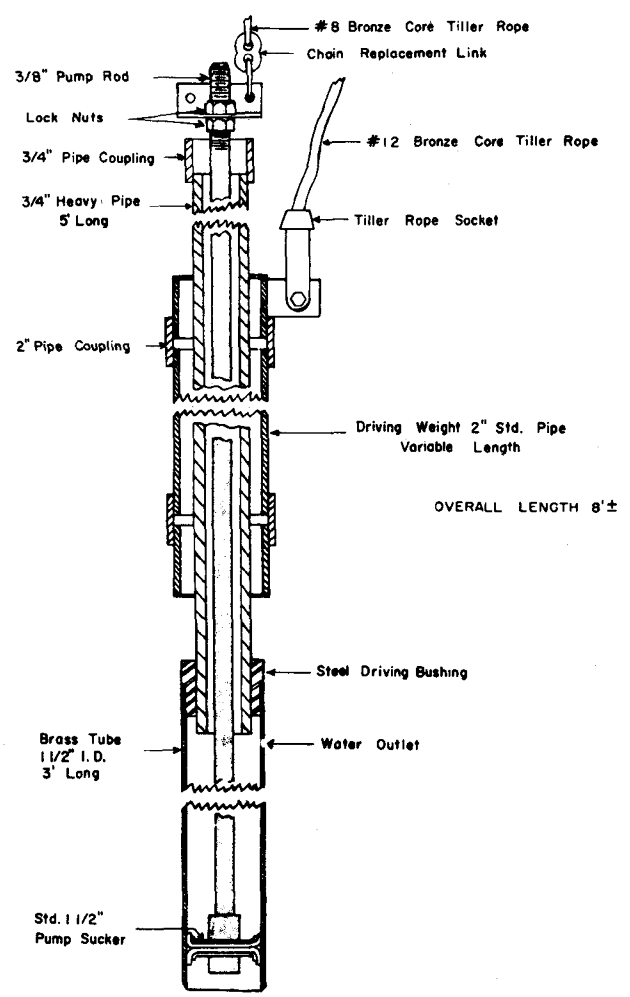


Figure 7–7.—Piston-type sediment-sampling tube.

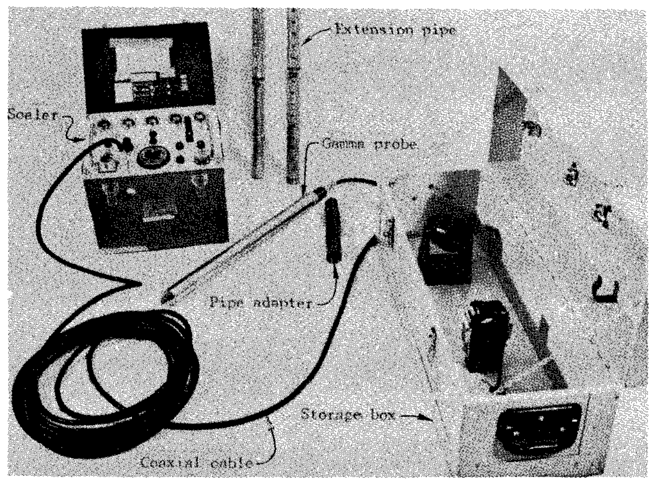


Figure 7–8.—Sediment density probe.

Survey Methods

The two currently used methods of determining the sediment volume and capacity of a reservoir are the contour and range methods. Choice of a method depends on the availability and character of base maps, purpose of the survey, and degree of accuracy desired.

The principal advantage of the contour method is that it shows both vertical and horizontal distribution of sediment and permits capacity curves to be plotted. On the other hand, it may require more observations than the range method and generally requires a longer period of survey. For small reservoirs, the contour interval should not exceed 2 ft. Random spudding, with the locations indicated on a base map or photograph, can provide enough depth measurements to produce a contour map for very small stock ponds.

Original contour maps of existing reservoirs often fail to include enough topographic detail to ensure accurate determination of capacity. Measurements of sediment volume made by subtracting the capacity determined by new contour surveys from that determined in previous surveys include errors caused by differences in survey accuracy.

The range method often requires less survey time than does the contour method and permits frequent, precisely located, and often more representative measurements of sediment thickness. By using permanent range-end monuments, the same points can be remeasured during future surveys to determine the sediment accumulation rate more accurately. The range method is preferable on delta areas if the original cross sections can be established by borings or from known elevations in the old valley.

The two methods can be combined if the ranges are located close enough together to construct an adequate contour map. By sounding water depth and probing or spudding sediment depth, accurate original contour maps and present contour maps can be constructed. The modified prismoidal formula (eq. 7–9) can be used to compute capacity. This formula provides area-capacity as well as stage-capacity information that cannot be acquired by using the range method.

In northern states, field data for the submerged portion of reservoirs can be collected by boat during warm seasons and through ice in winter in areas where ice becomes thick enough to support personnel and equipment. Some periods of mild weather usually occur in late winter when the ice is still thick enough. If surveys through ice are planned, keep the equipment ready for use so that the survey can be made without delay if the weather becomes mild.

Prepare a shoreline map if an adequate one is not available. In some places, making minor adjustments in the shoreline contour of an existing map is all that is needed. In other places, it will be necessary to map the shoreline. Aerial photographs are most convenient and are usually adequate for use in establishing the shore map. These maps are used primarily to locate survey stations for future reference and to determine the surface area for computing water and sediment volumes. Use only the center areas of aerial photographs, since inaccuracies caused by parallax occur near the edges. Enlarge the photographs to a convenient scale, such as 1 in. = 500 ft for large reservoirs and 1 in. = 200 to 400 ft for small reservoirs. If the water level was at spillway elevation the day the photograph was taken, the shoreline can be determined from the photograph. Otherwise, the shoreline contour can sometimes be determined by using a Kelsh plotter. Gage readings are available for some reservoirs and can be used to establish the water surface elevation on the day the photograph was taken. To ensure accuracy, check the scale of each photograph in the field by chaining the distance between objects identified on the photographs.

Range Survey

SCS uses the range survey method more often than the contour survey method because much SCS work is on small and old reservoirs for which good original maps are not available. A range survey can be made in less field time than a contour survey. The range method consists of laying out representative ranges (fig. 7–9) and determining the present water and sediment depths at intervals along these ranges. More frequent soundings at the channel section will define its often irregular profile more sharply. The number and location of the ranges depend on the shape and size of the reservoir. Use a minimum of three ranges for even the smallest reservoir. Subdivide the main body of the reservoir and its principal tributary arms into ranges so that sedimentation condition in each segment is represented, insofar as possible, by the average of conditions on the bordering ranges. Generally, locate the first range for earth fill dams at the upstream toe of the dam. Begin the series of ranges on the main body of the reservoir with this range and continue upstream to the head of the reservoir, keeping the ranges approximately parallel. For convenience, a divergence of 10 degrees or less between ranges can be tolerated in locating them, but more than 30 degrees should not be permitted except for a situation described in the next paragraph.

In some places the bends or curves in the reservoir will not permit such a limit of divergence for the entire series. If so, divide the series into sets at points where the limit of divergence can be maintained within each set. In segments between the sets, the ranges may diverge no more than 90

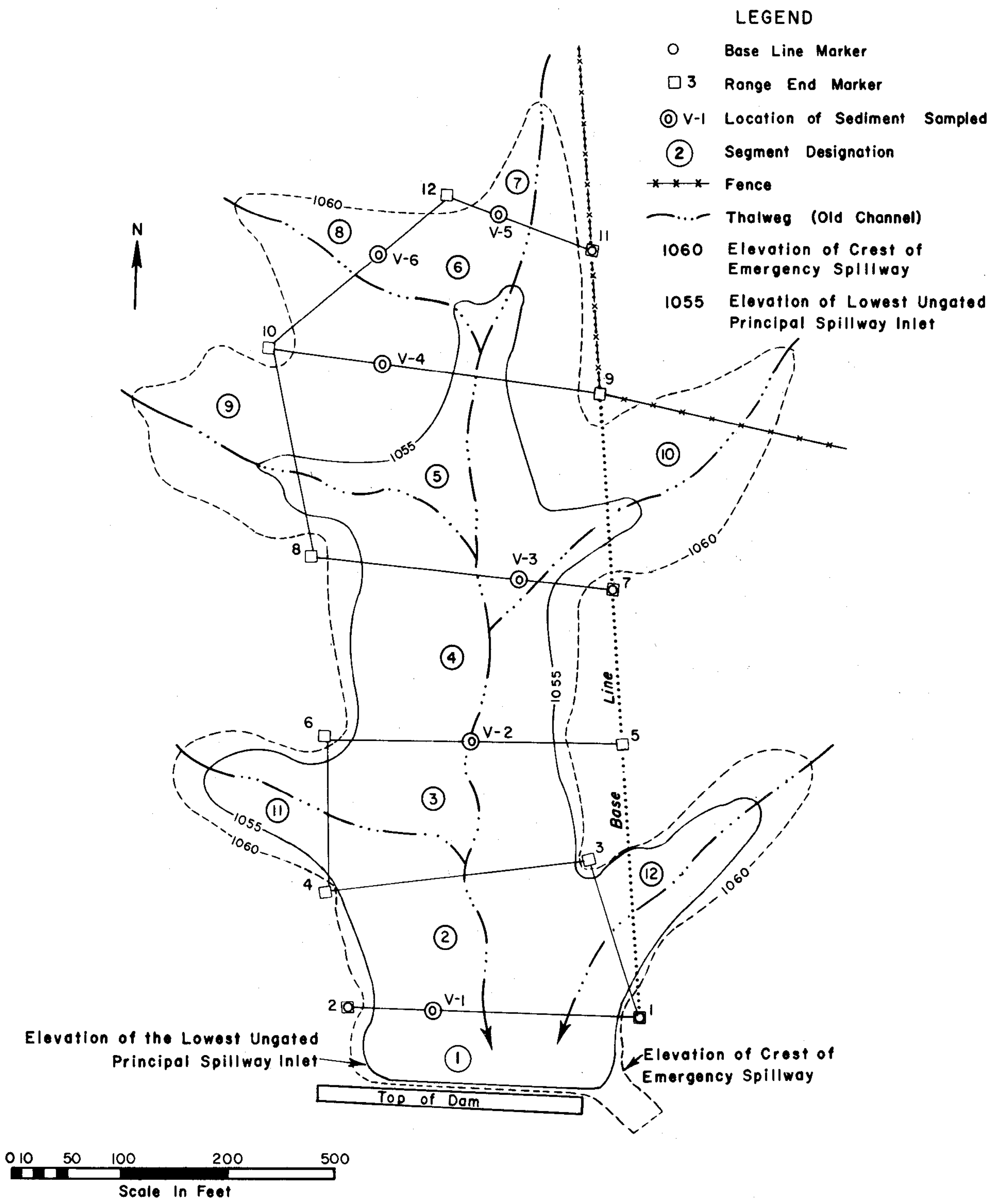


Figure 7-9.—Example of range layout.

degrees. In these transition segments, it is best to set the end ranges very close together or to start them from a common point to concentrate the irregularity into the smallest area so that it has the least effect.

For each major tributary or arm of the reservoir, start a new series of ranges without regard to the direction of the ranges on the main body of the reservoir. Lay out the first range across the mouth of the tributary or arm as nearly perpendicular to the general direction of the arm as practical.

If resurveys are expected, mark the end of each range with a permanent marker, such as a reinforced concrete post similar to those used to mark a highway right-of-way, or a steel or iron pipe set in concrete. A 4-in.^{2} reinforced concrete marker about 4 ft long is generally satisfactory. Set the markers into the ground deep enough that they will not be affected by frost action. The top of the markers should extend only far enough above the ground for ease in locating them again. Get permission from the landowners before setting the markers. Where possible, place markers along a fence line or other similar location to avoid any interference with field operations. Always set range markers above the shoreline for convenience in locating them again.

Reference the markers to a base line by instrument surveys so that they can be reestablished for future sedimentation surveys. Whenever it is known before a new dam is closed that sedimentation studies will be made later, it is desirable to locate the range ends and make instrument surveys of the ranges before the reservoir is flooded. In mountainous areas where large-size material is a significant part of the sediment delivered to a sediment pool, an original survey of the pool area is particularly important. If the particles are larger than sand, determining the original bottom of the reservoir by probing or sounding is impossible or, at least, extremely difficult. Inspecting the reservoir basin before flooding is very useful in determining range locations and observing and measuring breaks in slopes. If there are borrow areas within the basin, delineate them accurately. Smooth the borrow areas and other irregular areas in the reservoir before the construction equipment leaves the site.

The following system is recommended for identifying ranges, range markers, and reservoir segments. Identify ranges by number, beginning at the downstream range and continuing upstream to the upper end of the main body of the reservoir. Continue the numbering in consecutive order up each tributary, starting with the tributary farthest from the dam and proceeding to tributaries downstream.

Identify the range-end markers by number, beginning with the range nearest the dam and proceeding consecutively upstream in the same numbering order as for the ranges. For the first range, for example, the markers are "1" and "2". Show the assigned identification number on each marker. A brass plate imbedded in the top of the concrete marker during casting is a good place to stamp the identification. Other methods can be used, but each marker should be permanently identified.

Identify the reservoir segments by number, beginning at the segment adjoining the dam and continuing upstream.

When using the range method, measure the water depth and sediment thickness along each range. Secure the reel with cable or the end of the cable at one end of the range and assemble all necessary equipment in the boat. Fasten one end of the cable to a tree on the range line or to some other anchor, such as an auger or steel post. Take the free end across the reservoir to the other end of the range. During the crossing, attach floats to the cable to keep it on the surface of the water. If the reel has been transported, remove it from the boat and anchor it on the range line. Then tighten the cable. Keep the line meter with the cable running through it attached to the boat. Determine the range profile from the range end to the water surface by using a hand level or survey instrument and rod. Measure the distance from the range end to the line meter and set the meter to show that distance. Move the boat along the cable to the other end of the range. The line meter will show the distance from the range end at any point along the cable. Measure and record the water depth at each point where the sediment is measured directly, and record the distance between each observation point and the range end. Space spud or sounding pole observations as uniformly as possible to facilitate manual computation of range areas. If computation is to be done by computer, uniform spacing is not necessary. Space observations at intervals of 25 ft or less, depending on range length and irregularity of the reservoir bottom. Make at least 10 measurements on ranges more than 50 ft long. For example, for a range 150 ft long, 10 measurements at 15-ft intervals, plus any additional measurements necessary because of irregularities of the reservoir bottom, are adequate. Spacing can exceed 25 ft on ranges 250 ft or more long. The measurements should be made as previously described. Check frequently with the spud those measurements made with a sounding pole. Record the information for each measurement in a field book as explained under "notekeeping."

On reaching the opposite shoreline, obtain the profile to the range end by the same method used when starting the range profile. After all the readings have been recorded, release the tension on the cable and rewind the cable on the reel. Be careful when releasing cable tension. Follow the same procedure for all ranges. For convenience in comparing the profiles, it is desirable to start all measurements from the same side of the reservoir. Label each range according to the direction in which it is run, such as 2 to 1 or 14 to 15.

The principal difference in the procedure for making surveys through ice is that the distance from the range end to the soundings is measured at the surface of the ice with tape, chain, or stadia instead of with the cable and meter used in a boat survey. Between range markers measure and sight-in the distance from the range marker to the points at which soundings are to be taken. then cut holes through the ice large enough to accommodate the sounding pole, spud, sediment sampler, or other equipment.

Contour Survey

This method is usually used by SCS for surveys of reservoirs in which the original contour maps are highly accurate, the sediment cannot be penetrated by ordinary methods, or the sediment is thick enough to eliminate the possibility of large errors caused by any inaccuracy in the original maps (Gottschalk 1952). This method requires establishing elevations on the present sediment surface and drawing the contours. The area enclosed by each contour is planimetered and the volume computed according to the contour interval. To prepare a contour map of the sediment surface, take enough accurately located soundings to provide a basis for interpolating contours. The greater the irregularity of the surface, the greater the number of soundings required. Various methods can be used to determine the location of the soundings.

Any of several sounding patterns such as radial, grid, or closely spaced ranges, can be used. If later surveys are planned, prepare an accurate after-construction contour map.

Contour-Range Survey

This method requires both a contour map and cross sections (ranges) of the original reservoir to establish the original reservoir volume and cross-sectional areas. Sedimentation surveys are made by resurveying these ranges and relating the changes in segment volume to the proportional change in the cross-sectional area of the ranges. The segments are bounded by ranges, as in the range method, but the ranges need not be parallel and segments need not be uniform between the bounding ranges. Only water depth is measured on resurveys.

Measuring Thickness of Sediment

To measure sediment thickness with a spud, hold the spud vertically and throw it into the water with enough force to penetrate to the original bottom materials of the reservoir. If the spud cannot be withdrawn from the bottom material without considerable effort, snub the spud line to the boat and rock the boat until the spud is worked loose. Raise the spud through the water slowly to prevent washing off the sediment. Determine the sediment thickness by inspecting the deposit and the original bottom material trapped in the cups of the spud or adhering to the outside of the spud. Clean the spud thoroughly after each use. An ordinary scrub brush is adequate for this purpose.

If loose fine sediment does not adhere to the spud, use a steel reinforcing bar coated with concrete or other material with a rough surface. A medium to coarse sand mix is best. A mixture of quick-setting waterproof epoxy cement and sand or dark grits such as silicon carbide gives a durable surface to which sediment will readily adhere.

During such measurements both the present and the original depth of water can be determined. Determine the present depth of water by subtracting the sediment thickness plus the depth of penetration into the original bottom material from the water surface reading on the line. The original water depth equals the water surface reading on the line minus the depth of pentration into the original bottom material. Another method of determining the original depth is to determine the present water depth and add the sediment thickness as measured on the spud or reinforcing bar. Make the necessary adjustments for any difference between the water surface elevation at the time the measurements are made and the elevation of the principle spillway.

When resurveying reservoirs, a combination of spudding and sounding is most accurate, especially if the sediment deposited since the previous survey is less than 1 ft deep and the bottom of the reservoir is irregular.

Under some conditions, a sounding pole can be used to measure sediment thickness if the upper surface of the sediment is perceptible. If conditions are favorable, considerable time can be saved by using a sounding pole instead of a spud. Successful use of a sounding pole requires the ability to distinguish the sediment from the original bottom materials according to the difference in compaction. The surface of the sediment can usually be identified as the pole is lowered into the water. Determine the present water depth by taking a reading when the pole touches the surface of the sediment. Then push the pole down through the sediment to the more resistant original bottom material to measure the original water depth. The difference between the present and the original water depth is the sediment thickness. A sounding pole is most useful for measuring deposits of silt and clay because these deposits are usually less compact than the underlying bottom materials. Use of a sounding pole is normally limited to a sediment thickness of 10 ft or less, depending on the diameter of the pole and the character of the sediment.

In most reservoirs, sediment in shallow water has been exposed at one time or another to aeration, which can cause a hard crust to form. The crust can be mistaken for the old soil surface if only a sounding pole is used for measurements. It is therefore necessary to check sounding pole measurements regularly with a spud. This can be done if the deposits are not too thick. An auger can be used for greater depths of compacted sediment; additional 5-ft lengths of pipe can be added as needed. An auger is also suitable for determining the thickness of exposed deposits such as delta deposits.

Sampling for Volume-Weight of Sediment

Determine the volume-weight of sediment by taking a sample of known volume, drying it, and determining its dry weight. Report the results in standard units. Samples of exposed deposits can be taken with thin-wall push tubes, but samples of submerged deposits usually require a piston-type sampler. Take samples of exposed materials by forcing a push tube into the deposits to the desired depth; then remove the tube by excavating around it. The tubes can be capped and sent to the laboratory, or the samples can be extruded into other containers and sent to the laboratory.

Use a different procedure with the piston-type sampler. With the piston flush with the end of the sampling tube, lower the sampler from the boat to the sediment surface with ropes attached to the driving weight and to the piston rod of the sampler. Holding the rope attached to the piston rod in a fixed vertical position, usually snubbed over the side of the boat, drive the sampling tube into the sediment by raising and dropping the driving weight until the desired penetration is reached. Keep track of the depth of penetration. Mark the rope attached to the driving weight (see fig. 7–3) to prevent overdriving and consolidating the sediment sample. This provides a check on the length of the sediment sample obtained. Raise the sampler by pulling up on both ropes simultaneously. If the entire amount of extruded material is not required for analysis, select representative segments of the core. Measure these segments so that, together with the core diameter measurement, the volume of the sample can be computed. Each sample should contain at least a 0.3-ft length of core. Place the samples in pint jars or other containers and label them as to reservoir, location in reservoir, and diameter, length, and depth interval of the sample.

Send the samples to a laboratory to be dried and weighed and for additional analyses, such as grain-size analysis. The samples can be analyzed locally, sent to the materials testing section, or sent to the Soil Mechanics Laboratory at Lincoln, Nebr. The volume-weight of the sediment is needed to compute the weight of sediment accumulated in the reservoir. Mechanical analyses give the grain size for determining size distribution, calculating trap efficiency, and determining storage requirements in planning and designing floodwater-retarding structures.

During the field survey take enough sediment samples to determine representative specific weights for various segments of the reservoir. The number of samples required is determined by the size of the reservoir, character of material entering it, location and number of tributary streams, and extent of aeration. Indicate the location of each sample on the reservoir map (see fig. 7–9).

Direct Measurement of Volume-Weight

An instrument has been developed for determining the volume-weight of submerged sediment in place (Heinemann 1963). It is based on detecting the backscattering of gamma rays from a radioactive source. The instrument's response varies proportionally with the density of the material tested.

Some volumetric sampling is necessary to get specific gravity information for calibrating the gamma probe. Sediment samples must be taken if information on grain-size distribution is needed.

Notekeeping

Notekeeping for reservoir sedimentation surveys includes recording data on location, depth of soundings, and sediment thickness; descriptions of materials spudded and sampled; and all related information helpful in computing sediment volume and in preparing a report. Accurate and legible field notes are important for proper evaluation of the data.

It is equally important that notes be orderly and complete so that they can be evaluated in the field as well as in the office and followed years later, when a reservoir is resurveyed.

The bound Engineer Field Book, SCS–ENG–191, is recommended for keeping notes. The book can be carried conveniently in a pocket. The left-hand pages are divided into columns about 3/4 in. wide, adequate for recording numerical data. The right-hand pages are suitable for descriptions or sketches.

On the first page of the notes list the name of the reservoir, the nearest town, the date, the names of all personnel in the work party, and the water and crest elevation. Include on the first page any additional information available. For example, a plaque on the gatehouse or dam on a large reservoir may give information on the length of the spillway, the original capacity, the length of the lake, the spillway crest elevation, and the length of the dam at the top.

Record the weather conditions each day. General information on notekeeping is presented in Part 540 of the SCS National Engineering Manual and in Technical Release No. 62. If more than one boat is used in making measurements during a reservoir sedimentation survey, keep a set of notes in each boat. For example, if one boat is used to measure water depth and distance from shore and to tag the range cable for spudding and sediment sampling, keep complete notes of these measurements, including identifying data on fathometer charts. If the spudding and sediment sampling is done from a second boat, keep pertinent records on that boat.

In addition to the notebooks, keep a map of the reservoir showing its configuration and the range layout. If a previous survey has been made and a report published, a small-scale map showing the ranges and much helpful data on the reservoir and the watershed should be available. Aerial photographs of the reservoir will help in completing the survey and are available for most areas in the conterminous United States. Reservoir surface area is sometimes determined from aerial photographs.

Recording Measurements

It is traditional in range layouts to place odd-numbered range ends on the left side of the reservoir facing downstream. At the top of the page, identify the range. Start at the first range upstream from the dam with markers numbered 1 and 2. Then at the top of the page indicate R 1→2 or R 2→1, depending on the direction and order in which measurements are made. Range numbers must be shown in the proper sequence for later orientation to locate the thalweg and make comparisons. After the range cable has been run through the line meter and stretched across the range, record the horizontal distance from the marker to the shoreline. Then measure the distance from the shoreline to the line meter and set the meter to show the total distance from the marker.

If the shoreline at the time of the survey is not the same as the crest shoreline, determine the distance of these points from the range-end marker, since this information will be helpful later when reconstructing the cross section of the range. All measurements must be in terms of marker-to-marker distance. For example, if the distance from the marker to the crest shoreline is 10 ft, that to the present shore 2 ft farther, and that to the line meter another 7 ft, set the line meter at 19. The range can be run from marker 1 to marker 2 or vice versa as long as the notes give the correct sequence to orient the cross section.

Keep the records in tabulated form (see fig. 7–10). Head the first column "Station," and note the number of feet from the marker indicated; head the second column "Water Depth." Head the third column "Total Depth" and record the depth from the present water surface to the old soil surface, which is the sum of the water depth and sediment depth. Head the fourth column "Sediment Depth." In figure 7–10, the water level is at crest elevation. If the water level is not at crest elevation, make a correction in the fifth column, headed "Elevation of Original Bottom," to adjust the total depth to the original bottom elevation. Record the water-level elevation in the notes each day that sounding and spudding are done. If the water level fluctuates during the day, as on a power reservoir, record the time of the range survey and record the correct water level at that time; for example, Time—4:30 p.m., Water level—426.52 ft.

Record all depth measurements to the nearest 0.1 ft. If ranges or parts of ranges cross above-crest deposits, record the water depth as a minus figure. For example, if the sediment at the point of measurement is 1.2 ft above crest level or the present water level, record the present water depth as –1.2 ft.

Describe any sediment retrieved in the space to the right of column 5 under the heading "Remarks." Record the pertinent characteristics of the sediment, including type of materials, color, consistency, stratification, cohesiveness, thickness of homogeneous layers, and recognizable material

June 8, 1967 Sunny, hot 8:20 a.m. water surface elev. - 1055.0'

Mud Creek Reservoir

R2→1

Station	Water Depth	Total Depth	Sediment Depth	Elevation of Original Bottom	Remarks
0+00	–	–	–	1059.1	ground at range marker 2
+17	0.0	0.0	0.0	1055.0	elev. of lowest ungated principal spillway inlet
+37	1.0	1.0	0.0	1054.0	no sediment, old soil is yellowish-orange, clayey sand
+57	3.5	3.7	0.2	1051.3	dense, lt. gray, cohesive, silty clay, w/ leaf fragments, and sandy underlying old soil
+77	4.5	5.0	0.5	1050.0	" " " " " " "
+97	5.8	6.4	0.6	1048.6	same sediment, over rock bottom (cable tagged at 1+00 for sediment sample)
1+17	5.6	6.3	0.7	1048.7	same sediment over rock bottom
+37	5.8	6.2	0.4	1048.8	" " " " "
+57	5.7	6.2	0.5	1048.8	" " " " "
+67	7.8	9.0	1.2	1046.0	" " " " "
+77	7.9	9.4	1.5	1045.6	same sediment, not sure of old bottom
+87	6.0	6.6	0.6	1048.4	" " , sandy clay bottom
2+07	5.0	5.3	0.3	1049.7	" " " " "
+27	3.3	3.5	0.2	1051.5	" " " " "
+47	1.0	1.0	0.0	1054.0	" " " " "
+50	0.0	0.0	0.0	1055.0	elev. of principal spillway inlet
2+64	0.0	0.0	0.0	1060.2	ground at range-end marker 1
	W = 233'				LCG

Figure 7–10.—Notes from the measurement of a range.

such as mica, roots, and leaves. It is most important to note the geologist's interpretation of the boundary between the sediment and the surface of the original bottom, especially for spudding, since this is the basis for calculating sediment accumulation in the reservoir.

If the contour method is used, record notes on the base line layout and triangulation according to procedures given in standard surveying textbooks. If a plane table is used, record the information directly on the plane table sheet. Record sounding information and sediment descriptions as in range surveys.

No information is to be added to notes or plane table sheets obtained from the National Archives.

Sediment Samples

Samples must be identified. Record the following items about the samples in the notes: reservoir name, sample number, location of the sample in the reservoir in terms of distance from a station, date taken, total length of sample recovered, length of sample placed in the jar (to the nearest 0.1 in), and diameter of the sample. Record the reservoir name and sample number on the lid or elsewhere on the jar. Accurate measurements are required for meaningful volume-weight determinations. If a sample was obtained not on a range, note its location. Itemize the information about samples on a separate page of the notebook as in figure 7–11.

Fathometers

If a recording fathometer is used, record in the field book the measurements made at both ends of the range in shallow water with a sounding weight or pole. Because of inherent limitations in echo-sounding equipment, do not make measurements with this equipment in water less than 3 ft deep. To calibrate the fathometer at a depth exceeding 3 ft, check the echo-sounding measurement against the sounding-weight or -pole measurement.

Write the name of the reservoir, date, range, crest elevation, current water-surface elevation, and name or initials of the operator directly on the fathogram. Marking the fathogram with a vertical line every 10 ft and a heavy mark at 50 ft and every multiple of 50 ft is essential for horizontal control. Write the distance in feet directly on the fathogram along the vertical mark at least every 100 ft. Record the stationing for the beginning and end of the fathogram record on the fathogram. For the portion of the range not recorded insert in the field book: "See fathogram." To help in interpreting the fathogram, move the boat at a constant speed.

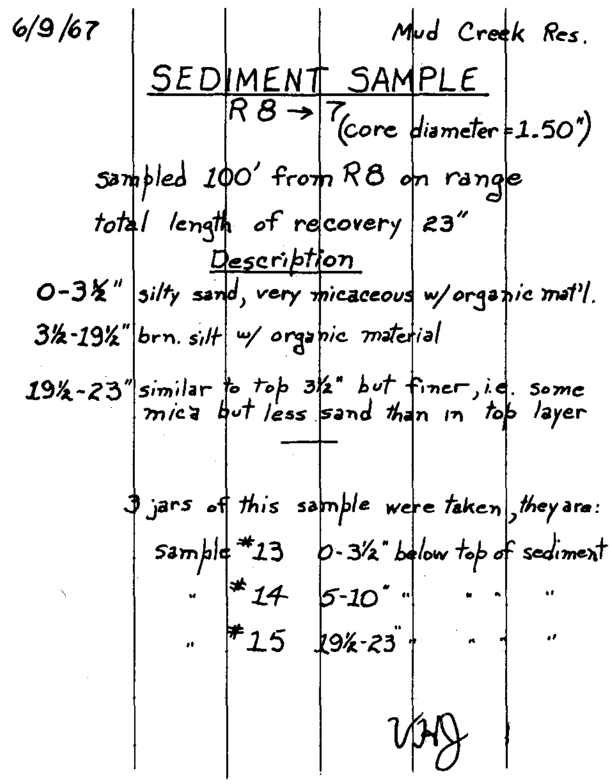


Figure 7–11.—Notes for sediment sample.

Computing Water Capacity and Sediment Volume

Because a reservoir is a complex three-dimensional figure, the accuracy of volume determinations reflects the amount of field and computation time invested.

The range method requires a minimum of field and computation time, but using the prisomoidal equation (eq. 7–3) in volume computations restricts the selection of ranges and segments. The ranges must be nearly parallel, and the segments should be uniform between main bounding ranges. If these requirements are not met, the prisomoidal equation does not furnish reliable answers.

The contour method requires a contour map of the original reservoir and a contour map for each resurvey. No restrictions are placed on field procedures, and data points can be random or ordered on ranges. It is, however, necessary to obtain enough data points for each sedimentation survey to construct an adequate contour map. Because of the field time required to obtain data for an adequate contour map and the office time required to construct the map and planimeter the areas, SCS seldom uses the contour method.

Range Method

After collecting the field data, determine the original area of the cross sections of the ranges and the area of the cross sections of sediment at each range to use in computing the original reservoir capacity and present volume of sediment. These areas can be computed directly from the field notes, or they can be determined by plotting the cross sections and planimetering the areas. The "computation" method is more accurate and saves considerable time by eliminating the time required to plot and planimeter the cross sections.

An example of the method used to compute the original area of cross sections for both capacity and sediment is shown in figure 7–12. The following equation can be used if the spacing of soundings or observations is not uniform. It permits summing the areas of individual trapezoidal slices, which are increments of the total area of the cross sections.

$$A = \frac{D}{2}(d_1 + d_2) \qquad \textbf{(7–1)}$$

Where

- A = area of trapezoid, square feet.
- D = distance between soundings, feet.
- d_1 = depth below reservoir crest at first observation, feet.
- d_2 = depth below reservoir crest at second observation, feet.

Summing the area of the trapezoids in the range cross section gives the total end area of the cross section, E, for the original capacity if the original water depth is used in making the computations, and the total end area of the cross section, E, for sediment if the sediment depth is used in the equation.

If the observations (soundings) are spaced fairly uniformly along the range, the following equation can be used in computing the area of the cross sections.

$$E = D_1\left(\frac{d_1}{2} + d_2 = d_3 \ldots \frac{d_n}{2}\right) + D_2\left(\frac{d_1}{2} + d_2 + d_3 + \ldots \frac{d_n}{2}\right) \text{ etc.} \qquad \textbf{(7–2)}$$

Where

- E = total area of the cross section of original capacity or sediment, square feet.
- D_1, D_2, etc. = distance between observations, feet. D_1 is the spacing used for one uniformly spaced group or series of observations; D_2, the spacing for another group or series of uniformly spaced observations; etc.
- d_1, d_2, ...d_n = original depth of water or sediment thickness below crest at each observation, feet.

Reservoir: Mud Creek — Range 2 → 1

Distance from Station	D (ft)	D/2 (ft)	d_1 (ft)	d_2 (ft)	d_1+d_2 (ft)	Area (sq. ft)	Accumulative Area (sq. ft)	
			Original Area					
0+17	0	0.0	0.0	0.0	0.0	0.0	0.0	
+37	20	10	0.0	1.0	1.0	10.0	10.0	
+57	20	10	1.0	3.7	4.7	47.0	57.0	
+77	20	10	3.7	5.0	8.7	87.0	144.0	
+97	20	10	5.0	6.4	11.4	114.0	258.0	
1+17	20	10	6.4	6.3	12.7	127.0	385.0	
1+37	20	10	6.3	6.2	12.5	125.0	510.0	
+57	20	10	6.2	6.2	12.4	124.0	634.0	
+67	10	5	6.2	9.0	15.2	76.0	710.0	
+77	10	5	9.0	9.4	18.4	92.0	802.0	
+87	10	5	9.4	6.6	16.0	80.0	882.0	
2+07	20	10	6.6	5.3	11.9	119.0	1001.0	
+27	20	10	5.3	3.5	8.8	88.0	1089.0	
+47	20	10	3.5	1.0	4.5	45.0	1134.0	
+50	3	1.5	1.0	0.0	1.0	1.5	1135.5	Original E
	W = 233′							
			Sediment					
0+17	0	0	0.0	0.0	0.0	0.0	0.0	
+37	20	10	0.0	0.0	0.0	0.0	0.0	
+57	20	10	0.0	0.2	0.2	2.0	2.0	
+77	20	10	0.2	0.5	0.7	7.0	9.0	
+97	20	10	0.5	0.6	1.1	11.0	20.0	
1+17	20	10	0.6	0.7	1.3	13.0	33.0	
+37	20	10	0.7	0.5	1.2	12.0	45.0	
+57	20	10	0.5	0.5	1.0	10.0	55.0	
+67	10	5	0.5	1.2	1.7	8.5	63.5	
+77	10	5	1.2	1.5	2.7	13.5	77.0	
+87	10	5	1.5	0.6	2.1	10.5	87.5	
2+07	20	10	0.6	0.3	0.9	9.0	96.5	
+27	20	10	0.3	0.2	0.5	5.0	101.5	
+47	20	10	0.2	0.0	0.2	2.0	103.5	
2+50	3	1.5	0.0	0.0	0.0	0.0	103.5	Sediment E
	W = 233′							

Figure 7–12.—Computation sheet for determining range area.

An example of the computation of the original area of the cross section from data in the field notes (fig. 7–10) and equation 7–2 follows. The d_1, d_2, ...d_n are from the third column in the notes, Total Depth:

$$E = 20\left(\frac{0}{2} + 1.0 + 3.7 + 5.0 + 6.4 + 6.3 + 6.2 + \frac{6.2}{2}\right) + 10\left(\frac{6.2}{2} + 9.0 + 9.4 + \frac{6.6}{2}\right) + 20\left(\frac{6.6}{2} + 5.3 + 3.5 + \frac{1.0}{2}\right) + 3\left(\frac{1.0}{2} + \frac{0}{2}\right)$$

$E = 1{,}135.5$ ft² (original capacity)

The sediment area is computed by equation 7–2 but d_1, d_2, ...d_n equal sediment thickness (fourth column of the notes) instead of original water depth:

$$E = 20\left(\frac{0}{2} + 0.2 + 0.5 + 0.6 + 0.7 + 0.5 + \frac{0.5}{2}\right) + 10\left(\frac{0.5}{2} + 1.2 + 1.5 + \frac{0.6}{2}\right) + 20\left(\frac{0.6}{2} + 0.3 + 0.2 + \frac{0.0}{2}\right)$$

$E = 103.5$ ft² (sediment)

The cross-sectional area of sediment below the crest elevation of the reservoir can also be computed from the computation sheets (fig. 7–12). Above-crest sediment deposits can be computed in the same manner. Record the area of all cross sections on Form SCS–ENG–209 "Reservoir Capacity Computation Sheet—Range Method" (figs. 7–13 and 7–14).

These examples illustrate the desirability of uniformity in spacing sounding observations from the standpoint of simplicity in hand computation.

In addition, water surface area, A, and the quadrilateral area, A′, must be determined for each segment. Both approximate the area enclosed by the ranges and intervening shoreline (crest elevation) bounding each segment of the reservoir. Reservoir segments can be bounded by any number of ranges and intervening stretches of shoreline. Segments with two ranges can have one or two stretches of shoreline, and areas with three or more ranges can be closed figures with no shoreline or can have any number of stretches up to the number of ranges. Determine the water surface area, A, by planimetering. Determine the quadrilaterial areas, which are formed by each set of main ranges and straight lines connecting the points where they intersect the shoreline at crest elevation, by computation. Computation of these areas is simple and fast. Scale the perpendicular distances, h_1 and h_2, between ranges and make the computations shown in steps 10 to 13 of figure 7–13. Step-by-step instructions for completing Form SCS–ENG–209, "Reservoir Capacity Computation Sheet—Range Method"; a filled-out example of this form; and a sketch of "h" distances are given in figures 7–13, 7–14, and 7–15, respectively.

The original capacity or sediment volume in each segment is determined by the Dobson prismoidal formula:

$$V = \frac{A'}{3}\left(\frac{E_1 + E_2}{W_1 + W_2}\right) + \frac{A}{3}\left(\frac{E_1}{W_1} + \frac{E_2}{W_2}\right) + \frac{h_3E_3 + h_4E_4 + \ldots}{130{,}680} \quad \textbf{(7–3)}$$

in which

- V = total original capacity or sediment volume, acre-feet.
- A′ = computed quadrilateral area of the segment formed on two sides by the main bounding ranges and on the other sides by lines drawn from the intersection of the range lines and crest contour, acres.
- A = segment area planimetered from base map, acres.
- E = cross-sectional area of water, sediment, or both along the range, square feet.
- W = width (length of bounding range) at crest elevation, feet.
- h = perpendicular distance from the range on a tributary to the junction of the tributary and the main stream or, if this junction is outside the segment, to the point where the thalweg of the tributary interesects the downstream range, feet (see fig. 7–15).

Subscripts used with E, W, and h indicate the respective ranges of the segment. For each segment, the range numbers (subscripts in the equation) generally are No. 1, the downstream range;

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

RESERVOIR CAPACITY COMPUTATION SHEET RANGE METHOD

SCS-209 (2-64)

______________________________ NAME OF RESERVOIR

SHEET ____ OF ____

$V = A'/3\,(E_1+E_2)/(W_1+W_2) + A/3\,(E_1/W_1+E_2/W_2) + h_3\,E_3/130{,}680 +$ ______

$V =$ V_1 + V_2 + V_3 ______

NUMERICAL INSTRUCTION				VERBAL INSTRUCTIONS				
1		SEGMENT NO.	GENERAL	SEGMENT NUMBER				
2		RANGE 1		DOWNSTREAM BOUNDING RANGE				
3		RANGE 2		UPSTREAM BOUNDING RANGE				
4		W_1		WIDTH DOWNSTREAM RANGE				
5		W_2		WIDTH UPSTREAM RANGE				
6	(4)+(5)	W_1+W_2		LINE (4) PLUS LINE (5)				
7	(6)X3	$3(W_1+W_2)$		3 TIMES LINE (6)				
8		h_1		PERPENDICULAR DISTANCE DOWNSTREAM RANGE TO SHORELINE UPSTREAM RANGE				
9		h_2		PERPENDICULAR DISTANCE UPSTREAM RANGE TO SHORELINE DOWNSTREAM RANGE				
10	(4)X(8)	h_1W_1		LINE (4) TIMES LINE (8)				
11	(5)X(9)	h_2W_2		LINE (5) TIMES LINE (9)				
12	(10)+(11)	$2A'$		LINE (10) PLUS LINE (11)				
13	(12)÷87,120	A'		LINE (12) DIVIDED BY 87,120 = COMPUTED QUADRILATERAL AREA OF SEGMENT IN ACRES				
14		A		SURFACE AREA OF SEGMENT PLANIMETERED FROM BASE MAP, IN ACRES				
15	(14)÷3	$1/3A$		1/3 OF LINE (14)				
16		h_3		PERPENDICULAR DISTANCE FROM SIDE RANGE TO THALWEG OF MAIN CHANNEL				
17	(16)÷130,680	$h_3/130{,}680$		LINE (16) DIVIDED BY 130,680				
18			ORIGINAL CAPACITY					
19		E_1		ORIGINAL END AREA OF DOWNSTREAM RANGE				
20		E_2		ORIGINAL END AREA OF UPSTREAM RANGE				
21	(19)+(20)	E_1+E_2		LINE (19) PLUS LINE (20)				
22	(21)÷(7)	$1/3\,\frac{(E_1+E_2)}{(W_1+W_2)}$		LINE (21) DIVIDED BY LINE (17)				
23	(19)÷(4)	E_1/W_1		LINE (19) DIVIDED BY LINE (4) = AVG. ORIG. WATER DEPTH AT DOWNSTREAM RANGE				
24	(20)÷(5)	E_2/W_2		LINE (20) DIVIDED BY LINE (5) = AVG. ORIG. WATER DEPTH AT UPSTREAM RANGE				
25	(23)+(24)	$(E_1/W_1+E_2/W_2)$		LINE (23) PLUS LINE (24)				
26		E_3		ORIGINAL END AREA OF SIDE RANGE				
27	(13)X(22)	V_1		LINE (13) TIMES LINE (22)				
28	(15)X(25)	V_2		LINE (15) TIMES LINE (25)				
29	(17)X(26)	V_3		LINE (17) TIMES LINE (26)				
30	(27)+(28)+(29)	V		$V = V_1 + V_2 + V_3$, ETC. ORIGINAL CAPACITY OF SEGMENT				
31			SILT VOLUME					
32		E_1		SEDIMENT END AREA OF DOWNSTREAM RANGE				
33		E_2		SEDIMENT END AREA OF UPSTREAM RANGE				
34	(32)+(33)	E_1+E_2		LINE (32) PLUS LINE (33)				
35	(34)÷(7)	$1/3\,\frac{(E_1+E_2)}{(W_1+W_2)}$		LINE (34) DIVIDED BY LINE (7)				
36	(32)÷(4)	E_1/W_1		LINE (32) DIVIDED BY LINE (4) = AVG. SED. THICKNESS DOWNSTREAM RANGE				
37	(33)÷(5)	E_2/W_2		LINE (33) DIVIDED BY LINE (5) = AVG. SED. THICKNESS UPSTREAM RANGE				
38	(36)+(37)	$(E_1/W_1+E_2/W_2)$		LINE (36) PLUS LINE (37)				
39		E_3		AREA OF SEDIMENT AT SIDE RANGE				
40	(13)X(35)	V_1		LINE (13) TIMES LINE (35)				
41	(15)X(38)	V_2		LINE (15) TIMES LINE (38)				
42	(17)X(39)	V_3		LINE (17) TIMES LINE (39)				
43	(40)+(41)+(42)	V		$V = V_1 + V_2 + V_3$, ETC. SEDIMENT VOLUME OF SEGMENT				
44								

Figure 7-13.—Instructions for computing reservoir capacity—range method.

RESERVOIR CAPACITY COMPUTATION SHEET RANGE METHOD

SCS-209 (2-64)

MUD CREEK
NAME OF RESERVOIR

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

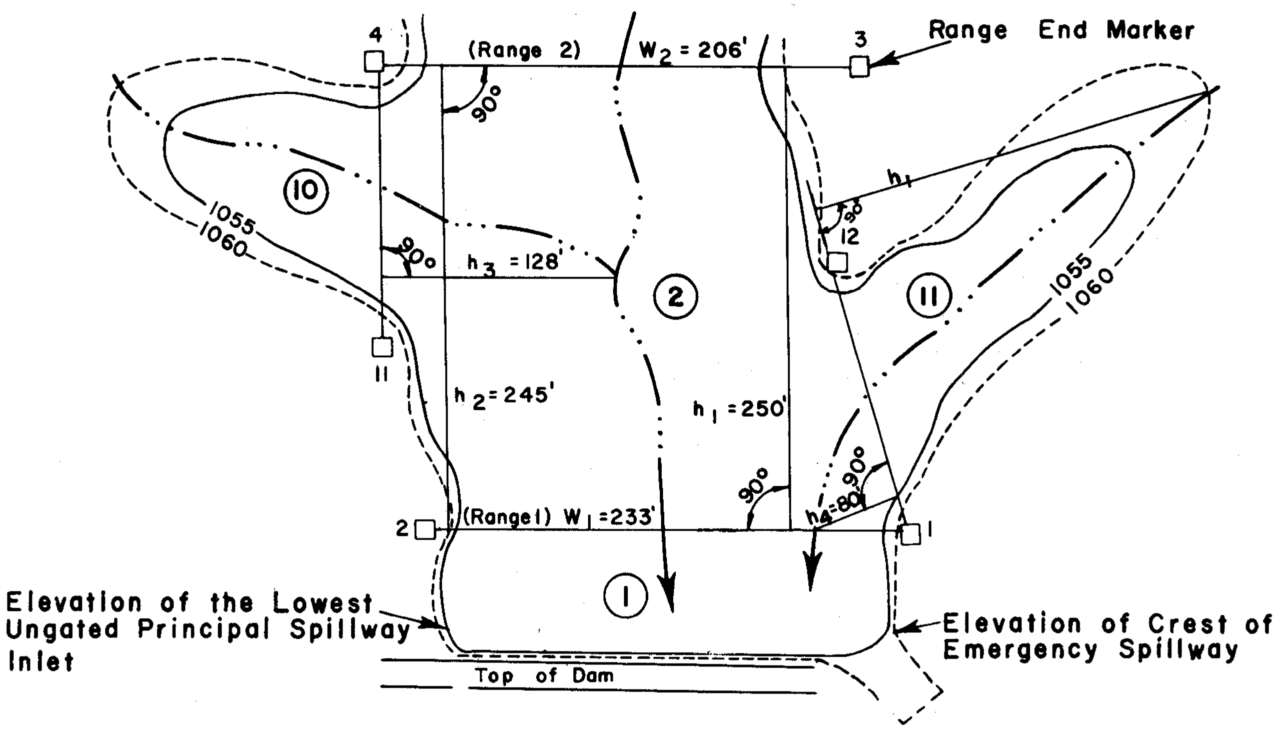
SHEET 1 OF 3

$V = A'/3\,(E_1+E_2)/(W_1+W_2) + A/3\,(E_1/W_1+E_2/W_2) + h_3 E_3/130{,}680 +$ ______

$V = \quad V_1 \quad + \quad V_2 \quad + \quad V_3$ ______

1		SEGMENT NO.		(1)	(2)	(3)	(4)	(11)
2		RANGE 1		Dam	2-1 (12-1)	4-3	etc.	12-1
3		RANGE 2		2-1	4-3 (4-11)	6-5		end
4		W_1			233.	206.		120
5		W_2		233	206.	240.		-
6	(4)+(5)	W_1+W_2			439.	446.		120
7	(6)X3	$3(W_1+W_2)$			1317.	1338.		360
8		h_1			250.	145.		235
9		h_2	GENERAL		245.	165.		-
10	(4)X(8)	h_1W_1			58250.	870.		28200
11	(5)X(9)	h_2W_2			50470.	39600.		-
12	(10)+(11)	2A'			108720.	69470.		28200
13	(12)÷87,120	A'			1.25	.80		0.32
14		A		1.38	1.29	.78		0.48
15	(14)÷3	1/3A		.46	.43	.26		0.16
16		h_3			128.	0		
17	(16)÷130,680	$h_3/130{,}680$			.00098	0		
18					80. .00061			
19		E_1			1155.5	800.		840
20		E_2		7608.	800.0	856.		-
21	(19)+(20)	E_1+E_2			1935.5	1656.		840
22	(21)÷(7)	$1/3\,\frac{(E_1+E_2)}{(W_1+W_2)}$			1.47	1.24		2.33
23	(19)÷(4)	E_1/W_1			4.87	3.88		7.00
24	(20)÷(5)	E_2/W_2	ORIGINAL CAPACITY	32.65	3.88	3.56		-
25	(23)+(24)	$(E_1/W_1+E_2/W_2)$		32.65	8.75	7.44		7.00
26		E_3 E_4			700. 600.	0		-
27	(13)X(22)	V_1			1.84	.99		0.75
28	(15)X(25)	V_2		15.02	3.76	1.93		1.12
29	(17)X(26)	V_3 V_4		V_o = 4.20	.69 .37			-
30	(27)+(28)+(29)	V		10.82	6.66	2.92		1.87
31								
32		E_1			103.5	70.0		56
33		E_2		103.5	70.5	95.0		-
34	(32)+(33)	E_1+E_2		103.5	173.5	165.0		56
35	(34)÷(7)	$1/3\,\frac{(E_1+E_2)}{(W_1+W_2)}$			.13	.12		0.16
36	(32)÷(4)	E_1/W_1	SILT VOLUME		.44	.34		0.47
37	(33)÷(5)	E_2/W_2		.44	.34	.40		-
38	(36)+(37)	$(E_1/W_1+E_2/W_2)$		.44	.78	.74		0.47
39		E_3 E_4			35. 20.			-
40	(13)X(35)	V_1			.16	.10		0.05
41	(15)X(38)	V_2		.54*	.33	.19		0.08
42	(17)X(39)	V_3 V_4		Vo = .22	.03 .01	0		-
43	(40)+(41)+(42)	V		.32	.53	.29		0.13
44				*Calculated by special formula				

Figure 7-14.—Computing reservoir capacity—range method.



h_1 = The perpendicular distance, in feet, from the downstream range to the shoreline at the upstream range on the right side looking upstream.

h_2 = The perpendicular distance, in feet, from the upstream range to the shoreline at the downstream range on the right side looking downstream.

h_3 = The perpendicular distance from the range on a tributary to the junction of the tributary with the main stream.

h_4 = The perpendicular distance from the range on a tributary to the point where the thalweg of the tributary intersects the downstream range.

Figure 7–15.—Methods of determining "h" values.

No. 2, the upstream range; and No. 3 and higher, ranges on tributaries or arms of the reservoir. If the range on a tributary is more nearly parallel to the downstream range than is the upstream range, the tributary range can be taken as No. 2 and the upstream range as No. 3.

This general equation applies to all reservoir segments except the segment next to the dam in which the effect of the shape of the dam does not lend itself to inclusion in the formula. Since this formula applies mostly to segments with an irregular shoreline and applies only to ranges that are nearly parallel, the average end-area equation 7–4 gives more reliable results for curved segments with a regular shoreline:

$$V = \frac{A}{2}\left(\frac{E_1}{W_1} - \frac{E_2}{W_2}\right) \tag{7–4}$$

Apply the equations for sediment volume the same way as for original capacity and give each variable, except E, the same value. If there is only one range in a segment, as on a tributary or reservoir arm, consider the upstream range as a point at the extreme upper end of the arm. In this case the upstream range has zero cross-sectional area ($E_2 = 0$) and zero width ($W_2 = 0$), although the quadrilateral area (A′) is not zero. Here A′ has one side (W_2) measuring zero and has the shape of a triangle in which W_1 is the base and the point of hypothetical range No. 2 is the apex. In this case the equation becomes:

$$V = \frac{A'}{3}\left(\frac{E_1}{W_1}\right) + \frac{A}{3}\left(\frac{E_1}{W_1}\right) = \frac{A' + A}{3}\left(\frac{E_1}{W_1}\right) \quad \textbf{(7–5)}$$

$$V = \frac{2}{3}\left(\frac{AE_1}{W_1}\right) \text{ (can be used when } A = A'\text{)} \quad \textbf{(7–5a)}$$

Compute the original capacity and sediment volume for the segment next to the dam, which has only one range, by the equation

$$V = A\left(\frac{E}{W}\right) - V_0, \quad \textbf{(7–6)}$$

where the values for V, A, E, and W are as previously defined and V_0 is the volume, in acre-feet, displaced by the upstream face of the dam. For concrete dams with a vertical or nearly vertical upstream face, $V_0 = 0$. The form, "Reservoir Capacity Computation Sheet—Range Method," on pages 7-21 and 7-22 was not designed for computing volume for the segment nearest the dam, but where $V_0 = 0$, it can be adapted. If there is an upstream slope on the dam and no berm, the volume for the segment can be computed as shown below. The data and computations should appear on calculation sheets with the data and computations for the other segments. For original capacity

$$V_0 = \frac{HBL}{261{,}360} \quad \textbf{(7–7)}$$

and for sediment volume

$$V_0 = \frac{L\left(2B - \frac{EB}{WH}\right)E}{174{,}240W},$$

where E and W are as described for equation 7–3 and:

- L = length of waterline on the face of the dam, feet.
- B = perpendicular distance from the downstream range to the waterline on the face of the dam, feet.
- H = waterline elevation minus the elevation of the old streambed directly below waterline on the face of the dam, feet. If the elevation of the old streambed at this location is not known, use the maximum original depth on the downstream range.

The sum of the original capacities and the sum of sediment volumes for all segments give the total original capacity and total sediment volume, respectively, at the time of survey.

A computer program is available to perform computations by either the Dobson prismoidal formula (eq. 7–3) or the average end area equation 7–4 and equations 7–7 and 7–8. Since hand computations are tedious and prone to error, computer processing is recommended where feasible. Instructions are available from the NTC sedimentation geologists.

Contour Method

For the contour method of survey, the first step in determining sediment volume is to plot the water depths on a reservoir map. Then draw in the present contours of the reservoir basin and determine the area enclosed by each contour by planimetering. The present capacity can be computed either for a segment of the reservoir bounded by one or more ranges and intervening stretches of shoreline or for the reservoir as a whole bounded only by the shoreline. If the original capacity is not known, make an original contour map by adding present water depths and sediment depths and plotting them. Computation is as described for present capacity in the previous paragraphs. Use the following modified prismoidal equation (Eakin 1939) for the computation:

$$V = \frac{L}{3}(A_l + \sqrt{A_l A_u} + A_u) \quad \textbf{(7–9)}$$

where

- V = original capacity or present capacity, acre-feet.
- L = contour interval, feet (in the lowest prismoid, L is the vertical distance between the lowest contour and the lowest point in the bottom of the reservoir).
- A_l = area of the original lower contour in determining original capacity or area of the present lower contour in determining present capacity, acres.
- A_u = area of the original upper contour in determining original capacity or area of the present upper contour in determining present capacity, acres (in the upper-

most prismoid, A_u is equal to the area enclosed by the crest contour).

Apply this equation progressively to the prismoids, beginning with the prismoid between the lowest contour and the bottom of the reservoir. Summing the computed volumes will give the total capacity. Sediment volume is the difference between the original capacity and the present capacity. Use Form SCS–ENG–210, "Reservoir Capacity Computation Sheet—Contour Method" (fig. 7–16), in this computation.

Contour-Range Method

Compute the original volume of the segments from elevation-area data planimetered from the original contour map. Changes in volume in each segment are related to changes in the cross-sectional area of a single associated range. For example:

Segment original volume = 20 acre-ft
Original area of range cross section = 100 ft^2
Resurveyed area of range cross section = 90 ft^2
New segment volume = $20\left(\frac{90}{100}\right)$ = 18 acre-ft

Segment capacity loss = 20 − 18 = 2 acre-ft

The segment next to the dam is associated with its upstream bounding range. Each remaining segment is associated with its downstream bounding range.

A computer program is available to process computations for the contour-range method. This program computes vertical sediment distribution and designates sediment as submerged or aerated. Instructions are available from the NTC sedimentation geologists.

Land Surveys

This method of surveying reservoirs enables surveyors to maintain good control. The method requires laying out a measured base line and ranges.

Establish the base line along one side of the reservoir as parallel to the main valley as possible. For future resurveys, set permanent monuments on the centerline at one end of the dam and at the intersection of the centerline with the base line. Using a transit, establish the angle between the centerline of the dam and the base line. Chain the base line and set and tack-point stakes at regular intervals according to the range layout to be used. Make the base line long enough so that the last range crosses the stream channel close to the crest elevation of the emergency spillway. Additional ranges may be established upstream for above-crest deposits.

It may be necessary to turn the base line to keep it parallel to the main valley. Monument each turn in the base line. Locate the monuments where they will not be damaged or destroyed and where each can be seen from the preceding one to reestablish the base line as necessary.

Place the ranges as perpendicular to the valley as possible, and place the first range near the upstream toe of the dam. Start a pattern by placing the next range parallel to the first. Narrow the spacing near the upper end of the reservoir.

To supplement the contour information gained by surveying range lines, map the upper spillway contour and a selected lower contour. These contours provide excellent horizontal control.

Prepare a contour map by first plotting the water depths on the reservoir map. Then, using these depths and the known configuration of the basin as a guide, draw in the contours. Determine the acreage enclosed by each contour by planimetering. This can be done for a segment at a time, for several segments, or, in very small reservoirs, for the entire contour area. Then make the computations by the modified prismoidal formula (eq. 7–9). An alternative method of calculation (Heinemann and Dvorak 1965) is the stage-area curve method, which requires plotting a well-defined stage-area curve (see fig. 7–17). The area between such a curve and selected elevations on the ordinate represents the reservoir capacity between these elevations. For example, the capacity between elevations 1,050 and 1,052 of the reservoir shown in figure 7–18 is represented by the shaded area. This area can be planimetered and converted directly to capacity in acre-feet.

Although this type of survey takes longer than others, it can be accurate in measuring sediment and remaining capacity. It requires only one-tenth to one-fourth of the monuments needed to mark each range end, so less time is needed for setting permanent makers. Another advantage of the contour-range method, which is also true of the contour method, is that it yields area-capacity and elevation-capacity information. This information is not obtained in a range survey.

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

RESERVOIR CAPACITY COMPUTATION SHEET CONTOUR METHOD

SCS-210 (2-64)

MUD CREEK
NAME OF RESERVOIR

SHEET 1 OF 1

SEGMENT	CONTOUR	$V=L/3(A_l+\sqrt{A_l A_u}+A_u)$				V	ACCUMULATIVE VOLUME Acre-feet
		L/3	A_l	$\sqrt{A_l A_u}$	A_u		
all	1045.5						
	1046.0	.167	0.00	0.00	0.07	.012	.012
	1048.0	.667	0.07	0.19	0.49	.050	.062
	1050.0	.667	0.49	0.74	1.12	1.567	1.629
	1052.0	.667	1.12	1.47	1.93	3.015	4.644
	1054.0	.667	1.93	2.37	2.90	4.802	9.446
	1056.0	.667	2.90	3.41	4.00	6.877	16.323
	1058.0	.667	4.00	4.56	5.20	9.178	25.501
	1060.0	.667	5.20	5.79	6.45	11.632	37.133
					Original	capacity	37.133

Figure 7-16.—Reservoir capacity—contour method.

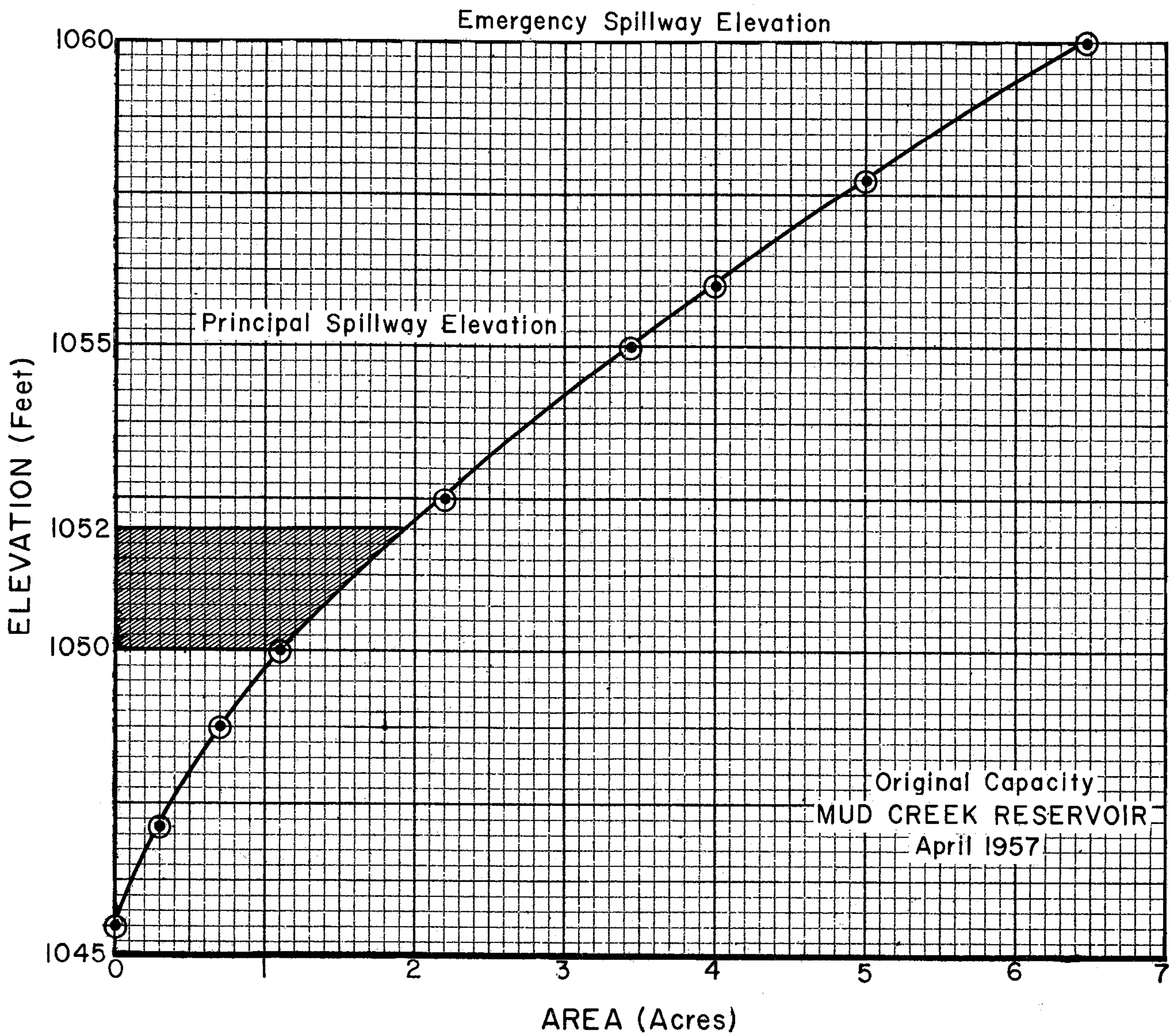


Figure 7–17.—Stage-area curve.

Survey Reports

After completing the computations, prepare a summary of survey data. Obtain enough information at the time of the survey to prepare Form SCS–ENG–34, Rev. 12–71, "Reservoir Sediment Data Summary" (fig. 7–18). Forward a copy of the completed form and a report, if one has been prepared, to the appropriate NTC for each reservoir surveyed.

A survey report is not always necessary, but if the information is readily available, a brief report of each survey may prove useful at some future date. Include in the report a brief description of the drainage area covering geology, topography and drainage, soils, land use and practices, and erosion conditions. Report land use as cropland, permanent pasture, woodland, idle, urban, or other. Get additional information for cropland, such as rotations in general use, conservation measures installed, and data so that sheet erosion can be computed.

SCS-ENG-34
REV. 12-71

RESERVOIR SEDIMENT DATA SUMMARY

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

Six Mile Creek, Site No. 3 — NAME OF RESERVOIR

23- — DATA SHEET NO.

DAM	1. OWNER Enlo Conserv. District	2. STREAM Six Mile Creek	3. STATE New State
	4. SEC. 25 TWP. 2N RANGE 4W	5. NEAREST P.O. 2 Mi. E of Nebo	6. COUNTY Carroll
	7. LAT. 45° 50′ 10″ LONG. 87° 07′ 30″	8. TOP OF DAM ELEVATION	9. SPILLWAY CREST ELEV. 123.0

RESERVOIR	10. STORAGE ALLOCATION	11. ELEVATION TOP OF POOL	12. ORIGINAL SURFACE AREA, ACRES	13. ORIGINAL CAPACITY, ACRE-FEET	14. GROSS STORAGE, ACRE-FEET	15. DATE STORAGE BEGAN
	a. FLOOD CONTROL	123.0	198.0	2,091.9	3,584.9	April 18, 1948
	b. MULTIPLE USE					
	c. POWER					
	d. WATER SUPPLY	111.0	124.8	1,002.0	1,493.0	16. DATE NORMAL OPER. BEGAN
	e. IRRIGATION					
	f. CONSERVATION					April 28, 1948
	g. INACTIVE	97.0	60.2	491.0	491.0	

RESERVOIR	17. LENGTH OF RESERVOIR 1.34 MILES	AV. WIDTH OF RESERVOIR 0.23 MILES
WATERSHED	18. TOTAL DRAINAGE AREA 10.14 SQ. MI.	22. MEAN ANNUAL PRECIPITATION 25.13 (25 yr) INCHES
	19. NET SEDIMENT CONTRIBUTING AREA 9.83 SQ. MI.	23. MEAN ANNUAL RUNOFF 1.6 (12 yr) INCHES
	20. LENGTH 5.17 MILES AV. WIDTH 1.96 MILES	24. MEAN ANNUAL RUNOFF 865. (12 yr) AC.-FT.
	21. MAX. ELEV. 398.0 MIN. ELEV. 76.0	25. ANNUAL TEMP.: MEAN RANGE

SURVEY DATA

26. DATE OF SURVEY	27. PERIOD YEARS	28. ACCL. YEARS	29. TYPE OF SURVEY	30. NO. OF RANGES OR CONTOUR INT.	31. SURFACE AREA, ACRES	32. CAPACITY, ACRE-FEET	33. C/I. RATIO, AC.-FT. PER AC.-FT.
4-18-48	--	--	Range-Contour (Detailed)	21 Ranges 2' CI	198.	3,584.9	4.14
6-23-64	16.18	16.18			198.	3,322.4	3.84
6-23-75	11.0	27.18			198.	3,202.0	3.70
6-23-81	6.0	33.18			198.	3,122.0	3.61

26. DATE OF SURVEY	34. PERIOD ANNUAL PRECIPITATION	35. PERIOD WATER INFLOW, ACRE-FEET			36. WATER INFL. TO DATE, AC.-FT.	
		a. MEAN ANNUAL	b. MAX. ANNUAL	c. PERIOD TOTAL	a. MEAN ANNUAL	b. TOTAL TO DATE
6-23-64	24.81	860	1,033	13,915	860	13,915
6-23-75	24.33	830	885	9,130	848	23,045
6-23-81	25.73	903	1,140	5,418	858	28,465

26. DATE OF SURVEY	37. PERIOD CAPACITY LOSS, ACRE-FEET			38. TOTAL SED. DEPOSITS TO DATE, ACRE-FEET		
	a. PERIOD TOTAL	b. AV. ANNUAL	c. PER SQ. MI.-YEAR	a. TOTAL TO DATE	b. AV. ANNUAL	c. PER SQ. MI.-YEAR
6-23-64	262.5	16.2	1.65	262.5	16.2	1.65
6-23-75	120.4	10.9	1.11	382.9	14.1	1.43
6-23-81	80.0	13.3	1.36	462.9	13.9	1.42

26. DATE OF SURVEY	39. AV. DRY WGT., LBS. PER CU. FT.	40. SED. DEP., TONS PER SQ. MI.-YR.		41. STORAGE LOSS, PCT.		42. SED. INFLOW, PPM	
		a. PERIOD	b. TOTAL TO DATE	a. AV. ANN.	b. TOT. TO DATE	a. PERIOD	b. TOT. TO DATE
6-23-64	67.4 (8)	2,423	2,423	0.45	7.3	20,380	20,380
6-23-75	69.4 (8)	1,789	2,166	0.39	10.7	14,670	18,480
6-23-81	68.8 (9)	1,948	2,126	0.39	12.9	16,280	17,930

Figure 7-18A.—Reservoir sediment-data summary.

26. DATE OF SURVEY	43. DEPTH DESIGNATION RANGE IN FEET BELOW, AND ABOVE, CREST ELEVATION											
	123–120	120–116	116–112	112–108	108–104	104–100	100–97	97–96	96–92	92–88	88–84	84–76
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN DEPTH DESIGNATION											
6-23-64	--	--	--	1	6	19	19	4	10	12	25	4
6-23-75	--	--	1	1	6	17	18	4	11	12	26	4
6-23-81	--	--	1	2	5	16	17	4	11	13	27	4

26. DATE OF SURVEY	44. REACH DESIGNATION PERCENT OF TOTAL ORIGINAL LENGTH OF RESERVOIR														
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	-105	-110	-115	-120	-125
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN REACH DESIGNATION														
6-23-64	2	17	19	14	17	10	9	5	7	0					
6-23-75	1	17	18	15	17	10	10	6	5	1					
6-23-81	1	18	19	16	16	11	9	5	4	1					

45. RANGE IN RESERVOIR OPERATION

WATER YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AC.-FT.	WATER YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AC.-FT.

46. ELEVATION–AREA–CAPACITY DATA

ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY
Original	Capacity	- 1948	100	75.3	658.0			
123	198.0	3,584.9	97	60.2	491.0			
120	178.4	2,832.0	96	58.0	442.3			
116	151.8	2,394.2	92	45.7	330.0			
112	128.9	1,679.0	88	32.1	265.7			
108	109.0	1,228.3	84	21.3	170.0			
104	94.2	931.9	80	11.7	73.0			

47. REMARKS AND REFERENCES

Land Use in Watershed: 21 percent Woodland; 47 percent Pasture; 18 percent Cropland; 6 percent Idle; 8 percent Residential.

Geology: 25 percent Chaco shale; 18 percent Thomas ls.; 57 percent Orville ss.

48. AGENCY MAKING SURVEY New State Watershed Planning Party, Soil Conservation Service

49. AGENCY SUPPLYING DATA Soil Conservation Service **50. DATE** Sept. 3, 1981

USDA-SCS-HYATTSVILLE, MD. 1966 April 1966

Figure 7-18B.—Reservoir sediment-data summary—continued.

For reservoirs of special interest, prepare a report so that the data can be made available to all who use them. Present the data and observations in a systematic, clear, concise arrangement and uniform style. The following outline is suggested. All the information included in the outline may not apply to a given survey and some may not have been obtained. Include any additional information that is considered important.

Outline

Abstract.—In a few paragraphs, summarize the important facts in the report, including a brief description of the reservoir, the watershed, the sediment deposits, the principal quantitative results of the survey, and the main conclusion.

Introduction.—Briefly state the purpose of the survey and the names of the survey party and participants, and acknowledge any assistance received.

General information.—Tabulations are means of presenting quantitative data and are desirable if they can be readily understood. Include the following items:

- Location
  - State
  - County (or counties); also sections, townships, and ranges where possible
  - Latitude and longitude
  - Distance and direction from nearest post office
  - Name of stream on which dam is located
- Ownership
- Purpose served
- Description of dam (type, construction material, length, height, sideslopes, elevation of spillways, and special features such as floodgates and character of foundation)
- Date dam completed (to nearest month; also average date of survey and total age to date of survey)
- Length of lake (from dam to head of backwater, and length of major arms in miles or feet)
  - Original ______
  - At time of survey ______
  - Amount shortened ______
- Area of lake at emergency spillway crest (acres)
  - Original ______
  - At time of survey ______
  - Loss from sediment deposition ______
- Storage capacity to principal spillway elevation (acre-feet)
  - Original ______
  - At time of survey ______
  - Loss from sediment deposition ______
- General character of reservoir basin
- Former sedimentation surveys (give details)
- Area of drainage basin (square miles or acres)
- General character of watershed
  - Geology
  - Topography and drainage
  - Soils
  - Land use
  - Erosion conditions
- Mean annual rainfall
- Mean annual inflow to reservoir
- Evaporation (if known)
- Draft on water-supply reservoirs (usual daily or monthly draft, season of greatest use, and draft during this period)
- Power development (where appropriate)
- Irrigation
- Method of survey
- Sediment deposits
  - Character of sediment. Describe the sediment in various parts of the reservoir and include the results of laboratory studies.
  - Distribution of sediment. Discuss the general distribution of sediment and, if feasible, illustrate with charts and graphs the average and specific depths of sediment in various parts of the basin. If the contour method was used, indicate sediment accumulation by contour intervals. Also discuss factors affecting distribution, such as configuration of basin, nature of incoming sediment, trap efficiency, drawdown, change in dam height, mass movement of sediment, and other factors whose effects are evident. Include any laboratory studies that concern distribution.
  - Sources of sediment. Describe the character and distribution of sediment in terms of source materials, slope, climate, land use, and erosion conditions. Discuss the relative importance of specific areas and soils in the watershed as sources of reservoir sediment.
  - Effects of land treatment. Describe conservation measures installed and the area in-

volved for each type. Give information about changes in land use. Include the effects of these items on sediment yield if this information is available.

Illustrations. Maps of reservoir and watershed, pertinent photographs and graphs.

Conclusions.—All interpretations, conclusions, and recommendations based on the completed study of the sedimentation and watershed conditions (unless adequately covered previously) should be presented in a final section. A completed Form SCS–ENG–34, "Reservoir Sediment Data Summary" (fig. 7–18), should be included in this section. Detailed instructions for filling out the form are available from the NTC's.

Send a copy of the completed Form SCS–ENG–34 to the NTC sedimentation geologist to keep the NTC informed of the current status of basic data collection. This information is submitted periodically by the NTC's to the National Headquarters for compiling nationwide summaries of reservoir sedimentation surveys under the auspices of the Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, and for compiling SCS-wide progress reports.

Record Maintenance

File completed records for future reference. The disposition of records depends on the nature of the record and its expected use. Records of surveys can be retained in state office files.

Surveys made in connection with developing a particular watershed work plan can be incorporated in the specific watershed file. It is desirable that each state office maintain a list of all reservoir surveys and resurveys made within the State, including disposition of the data collected.

Survey records can be sent to the National Archives. Archiving of these records is encouraged, since they can then be incorporated with records of similar surveys made by SCS on several hundred reservoirs in the country.

No data or marks of any kind may be added to records borrowed from the National Archives for use in a resurvey.

Purpose and Objectives

A flood plain is an alluvial area adjacent to a stream and subject to overflow during high waters. Flood-plain damage surveys are made to obtain physical data on the extent of damage and the rate and degree of infertile deposition, swamping, streambank erosion, flood-plain scour, valley trenching, and aggradation and degradation of channels.

The major objectives of flood-plain damage surveys are to determine:

1. Damage to soil and other resources and depreciation in land values from accelerated (modern) sedimentation.
2. Effect of sedimentation on flood conditions and flood-control problems.
3. Relative importance of various erosion sources in contributing to bottom-land damages.
4. Physical facts necessary to evaluate and project the effects of possible sediment-control measures.

Attaining these objectives requires, in most surveys, measuring the depth and areal distribution of modern sediment and erosion, and determining the relative texture and productivity of the modern sediments and the older sediments.

Preliminary Sedimentation Investigations

If field inspection indicates that erosion and sedimentation damages are appreciable and must be determined before preparing a work plan, more intensive investigations are required.

A preliminary sedimentation investigation is the first step in evaluating sedimentation and erosion damages. In this preliminary investigation determine the general extent and nature of sedimentation and erosion damages in the area considered and the approximate limits of subareas within which conditions are nearly the same. Select representative areas within the problem region for detailed sampling and investigation. Also determine whether location, rates, and kinds of deposition in the flood plain represent present conditions or whether measurement may not reflect substantial recent changes in the watershed, such as large increases or decreases in channel capacity or sediment supply by natural or artificial means. These findings determine the location and interpretation of detailed flood-plain sedimentation surveys.

Also include in the preliminary investigation a search for any available survey records containing data that can be compared with present conditions to measure the rate of channel or valley aggradation or harbor filling. These survey records may be highway or railway bridge cross sections or surveys for navigation, levee construction, drainage, irrigation, or other engineering purposes.

Make a traverse of representative parts of the area and examine the valley conditions. Make test borings and examine streambanks and other exposures that show the vertical sequence of flood-plain deposits. At each location, record size and condition of the stream channel; nature of channel sediment; soil texture; land use; apparent productivity of agricultural land; indications of sediment deposition rates such as buried fenceposts and trees; and types of sediment damage and percentage of land involved in each type. Many random test borings are usually required. Determine the source of harmful sediment by inspecting the eroding areas and comparing them with the sediment deposits causing damage.

Inquire among local residents, landowners, public officials, and other informed persons for any pertinent information about sediment deposition rates, extent and nature of associated damages, and location of areas of particularly rapid or harmful deposition.

Detailed Sedimentation Investigation

Developing the Plan

If the preliminary sedimentation investigation indicates that the sediment damages are important enough to justify detailed investigation, prepare a plan for further investigation. Specify the types of investigations needed and estimate the personnel and time required. Include either a sketch map showing the generalized or tentative location of ranges, sampling-survey areas, and other work areas, or a summary listing the areas to be surveyed in detail, approximate numbers of ranges to be bored, and cross sections to be profiled.

Boring and Logging

Thickness and distribution of the modern deposits are usually important in determining the nature and extent of sediment damage. Therefore, the modern sediment deposits must be measured as a basis for estimating past damage and predicting future rates and trends of sedimentation and sediment damage. For valley deposits, make test borings at selected locations to measure the thickness of modern deposits or measure the surface elevations.

To provide optimum working conditions and avoid locations where local conditions could make identification of the thickness of modern deposits especially difficult, determine the exact location of test borings in the field. Locate borings to show major changes in configuration of the base of modern deposits.

Record pertinent information such as texture, color, presence or absence of concretions and other inclusions, depth to water table, acidity, and presence or absence of organic matter. For each test hole, estimate the depth to the base of the modern deposits and record it in the notes. Keep these records of boring either in a field notebook or on Standard Logging Form SCS–ENG–533. Include the date, the identification number assigned to each range and to each hole on a range, the approximate spacing and direction of numbering of holes, and the distance and direction of streambanks from the nearest holes. Also include the distance from the outer margins of flood-plain deposition to the nearest boring, the approximate location and bearing of the range, and a field location sketch.

Interpreting Test-Hole Data

The degree of damage to flood plains is usually determined from the test-hole data. Estimate the damage (to the nearest 10 percent) to the productive capacity of the original soil by determining the depth and texture of the deposited sediment and estimating the loss. As sediment depth increases and texture becomes coarser, the degree of damage increases. If the original soil was a highly productive silt loam, the damage caused by deposits of relatively infertile sands would be high. The same type of sediment deposited to the same depth on an original sandy soil low in organic matter, nitrogen, phosphorus, and potassium would cause less damage. Recovery of the new sediment to the original soil condition would be faster and the remaining damage would be lower than that for the silt loam soil.

Other means of determining the present damage are comparing crop yields on land on which sediment has been deposited with crop yields on similar land without any sediment deposits and interviewing owners or operators who can furnish information on reductions in their crop yields caused by sediment deposition.

Estimates of damage and recovery rates under flood-free conditions are shown in table 7–1.

In general, time for recovery increases with percentage of damage. Full recovery normally does not occur if the damage is 40 percent or more. It should be emphasized that estimates of recovery must be based largely on judgment, keeping in mind that both damage and recovery vary according to the kind of soil damaged and the type of sediment deposited.

Survey Methods

To obtain the most usable damage estimates, divide the flood plain into reaches. Because the geology, economics, hydrology, and hydraulics of the flood plain are interrelated, consult other members of the planning party in doing so. Make each reach as uniform as possible.

The two methods of determining the amount of flood-plain damage are the mapping method and the range method. The mapping method is used if sediment deposition or erosion is concentrated in small, scattered areas. If sediment deposition or erosion is widely distributed within the valley, the range system of survey provides more representative sampling. Both methods give similar results if damage is evaluated with a high degree of accuracy and consistency and if the selected ranges are representative. Estimates should be prepared in consultation with SCS specialists, representatives of cooperating agencies, and local residents.

Mapping Method

Mapping the flood plain is the most precise method for locating the damages. These surveys can be made on representative samples or on the entire flood plain. If the surveys are made on representative samples, expand the results to the entire area within the designated reach. If they are made on the entire flood plain, record the information by the designated reach.

Determine and map the extent, location, and percentage of flood-plain damage on a base, preferably aerial photographs. The following legend is satisfactory for such surveys and can be adapted to local conditions.

Deposition on Flood Plains
- 0 = No deposition
- 1 = 1 to 33 percent of area covered with damaging sediment
- 2 = 33 to 66 percent of area covered with damaging sediment
- 3 = 66 to 100 percent of area covered with damaging sediment

Swamping
- 0 = No swamping damage
- 1 = Bottom land formerly suitable for cultivation now too wet for crops but can be used for pasture

Table 7–1.—Flood-plain damage and estimated recovery period by depth and texture of sediment deposit

Sediment deposit: Depth	Sediment deposit: Texture	Damage	Recovery period	Damage remaining after recovery
Inches		*Percent*	*Years*	*Percent*
4–8	Fine and coarse sand and silt	20	5	0
4–8	Medium and coarse sand	40	10	10
8–12	Fine and coarse sand	40	10	10
12–14	Coarse sand	60	20	30
12–24	Coarse sand and gravel	90	30	50

2 = Bottom land formerly suitable for cultivation now too wet for agricultural use but suitable for timber

Scour

0 = No scour damage

1 = 1 to 33 percent of area scoured

2 = 33 to 66 percent of area scoured

3 = 66 to 100 percent of area scoured

Enter a three-digit mapping symbol, representing deposition, swamping, and scour in that order, in each delineated area of flood plain to indicate the location, type, and degree of damage. Also indicate the geologist's estimate of the physical damage caused by deposition or scour expressed as a percentage. Thus 1–0–0 (40 percent) indicates an area of flood plain of which 1 to 33 percent is covered with infertile sediment causing a 40-percent damage to that area; 0–2–0 indicates an area of flood plain that was previously cultivated but now, because of accelerated swamping, can support only woodland growth. Also record areas of no damage, 0–0–0, so that the damages can be correctly distributed to the entire flood plain.

Measure and tabulate the mapped information. Be sure to account for the area occupied by the channel. Figure 7–19 illustrates a flood-damage map. Table 7–2 shows how the mapped information has been tabulated. This example shows deposition and scour damage on the same areas each year and an increasing area of swamping. Various combinations can be expected in different damage areas.

Range Method

A range system sampling procedure is especially useful if the various types of damages are scattered along flood-plain reaches. Ranges are located randomly within the reach on the premise that a representative sample of the total flood plain will thus be obtained. Do not deliberately locate a range to cross either high or low damage points, to get out of a swamp onto high ground, or to get out of the woods into the open. Doing so could invalidate the entire survey. Although each range should be a straight line, the locations of bore holes or other observations can deviate several feet from this straight line for convenience.

Spacing of the ranges depends on the length of the reach and the regularity of damages within it. A minimum of three ranges per reach is desirable and a maximum of 15 is reasonable. The distance between ranges should not exceed 1 mile nor be less than 1/4 mile. About one-twentieth of the length of the valley under investigation is the usual distance between ranges, but spacing varies according to the conditions found in reconnaissance or during the detailed survey. Space the ranges closer where identifying the base of modern deposits is difficult or where the thickness of modern deposits is irregular. Where the base of modern deposits is easy to identify and the depth of deposits is fairly uniform, space the ranges wider. Locate the ranges on a base map.

Summarize the weighted sediment damage to the flood plain (by area) as shown in table 7–3 for Reach B as drawn in figure 7–19. Send this summary to an economist for monetary evaluation.

Insofar as practical, include the surveyed cross section used for hydrologic study in the flood-plain ranges. Where they are the same, the distance measurements can be obtained from the plotted cross sections. As a word of caution, the hydrologist needs cross sections at control points that may not be typical of flood-plain conditions. If the ranges do not include surveyed cross sections, pace the distance or use an aerial photograph as a base map to determine the distance. A minimum of four holes is usually required on each range. Generally, space the holes 100 to 300 ft apart in a valley 1 mi or less wide. Show the linear extent of each type of damage along each range and also record the percentage of damage.

Record all data on a field sheet as shown in table 7–4. Prepare a separate sheet for each range.

In summarizing the flood-plain data, first summarize the data on each field sheet. This can be done on a weighted-average basis or by individual increments, depending on the kind of data desired by the economist. Following is an example of data summarized on a weighted-average basis for damages caused by infertile deposits.

100 linear feet is damaged 10 percent by infertile deposits;

100 linear feet is damaged 20 percent by infertile deposits; and

50 linear feet is damaged 90 percent by infertile deposits

Total for range: 250 linear ft is damaged by infertile deposits. The weighted average damage is 30 percent, i.e.

$$\frac{(100 \times 10) + (100 \times 20) + (50 \times 90)}{250} = 30 \text{ percent}$$

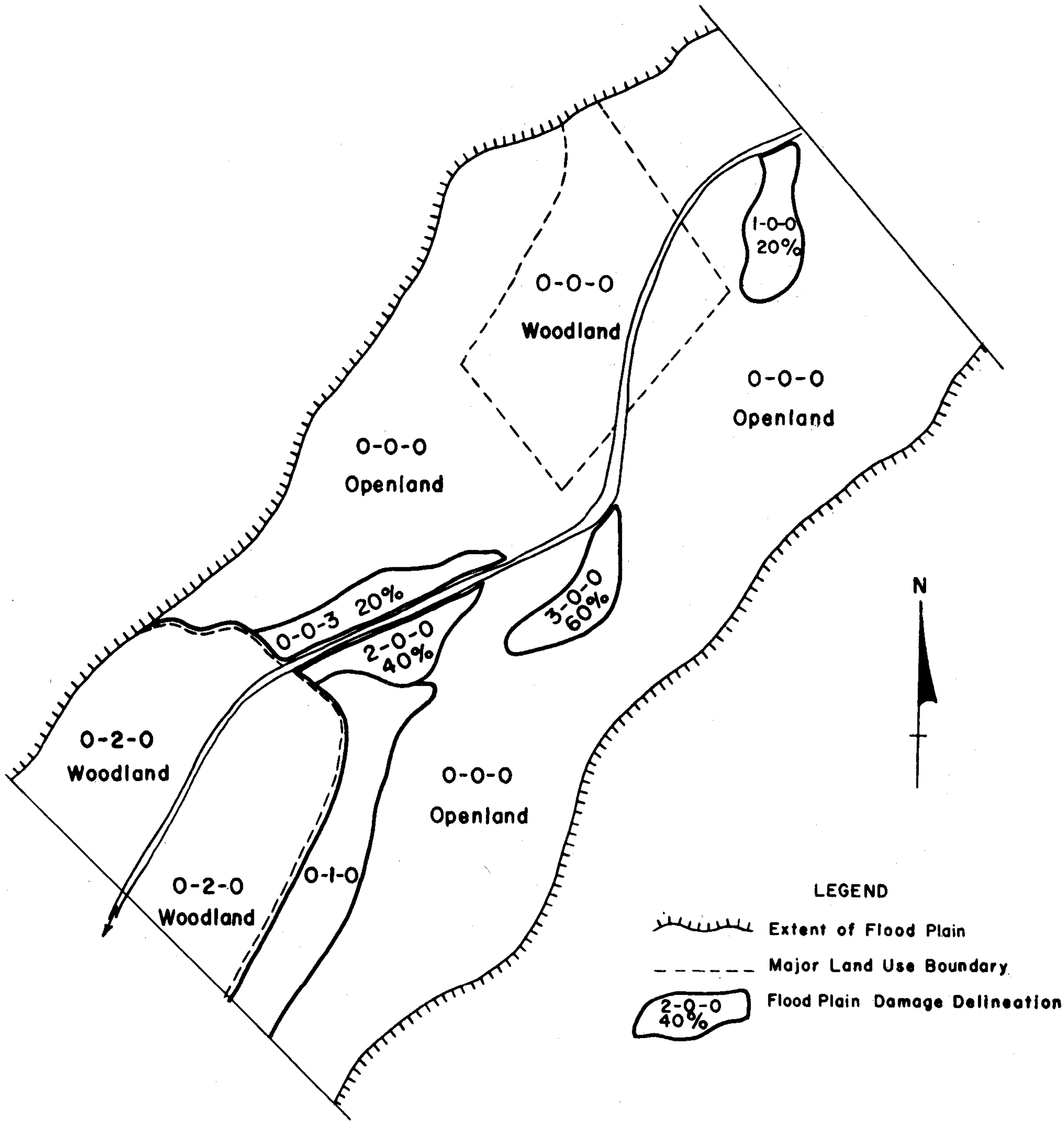


Figure 7–19.—Flood-plain damage survey.

Table 7–2.—Type and extent of physical land damage, Reach B

Extent	Type of damage							
	Deposition			Swamping		Scour	No damage
	1	2	3	1	2	3	
Area (acres)	7	7	6	23	77	8	300
Damage (percent). . .	20	40	60	—[1]	—[1]	20	—

[1]To be determined in consultation with the economist.

Table 7–3.—Summary of flood-plain damage, Reach B

Type of damage	Area	Period	Rate	Damage
	Acres	*Years*	*Acres/year*	*Percent*
Deposition	20	1	20	38
Swamping				
1	23	40	0.6	—[1]
2	77	40	1.9	—[1]
Scour	8	1	8	20

[1]To be determined in consultation with the economist.

Summarize other types of flood-plain damage in the same way.

Next summarize the damage within each reach. This is most easily done by using field summary sheets. Use a separate summary sheet for each reach and itemize the totals and weighted averages computed for each range in the columns. Summarize the columns, following the procedure used to summarize individual ranges, to determine the average range for each reach of flood plain (see table 7–5). Table 7–6 shows a method of computing average values for a reach.

Table 7–4.—Sample worksheet for range data summary

Range 1 Reach A

Mud Creek Watershed Survey

From station to station[1]		0–100	100–120	120–220	220–240	240–260	260–310	310–End	Totals and weighted average
Infertile deposits	Distance (ft)	100	—	100	—		50	—	250
	Damage (%)[2]	10	—	20	—		90	—	30
Swamping	Distance (ft)	—	20	—	—		—	—	20
	Damage (%)	—	40	—	—		—	—	40
Streambank erosion	Distance (ft)	—	—	—	20		—	—	20
	Damage (%)	—	—	—	90		—	—	90
	Average depth (ft)	—	—	—	3		—	—	3
	Net X-sectional area (ft²)	—	—	—	60		—	—	60
Flood-plain scour	Distance (ft)	—	—	—	—	Mud Creek Channel	—	—	—
	Damage (%)	—	—	—	—		—	—	—
	Average depth (ft)	—	—	—	—		—	—	—
	Net X-sectional area (ft²)	—	—	—	—		—	—	—
Valley trenching	Distance (ft)	—	—	—	—		—	—	—
	Damage (%)	—	—	—	—		—	—	—
	Average depth (ft)	—	—	—	—		—	—	—
	Net X-sectional area (ft²)	—	—	—	—		—	—	—
Texture	Gravel (%)	—	—	—	80		60	—	—
	Sand (%)	—	—	—	10		40	—	—
	Fines (%)	100	100	100	10				

[1]All measurements are from left side of valley looking downstream unless otherwise noted.
[2]To nearest 10 percent.

Table 7-5.—Computation of the weighted averages of types of damage, Reach A

1 Type of damage	2 Distance	3 Damage	4 Damage Factor (Cols. 2 x 3)		5 Averages
	Feet	*Percent*			
	250	30	7,500		(av. distance)
	210	30	6,300		$\frac{1,110}{5}$ = 222 ft
Infertile	260	20	5,200		
deposits	210	40	8,400		
	180	40	7,200		(wt. damage)
	1,110		34,600		$\frac{34,600}{1,110}$ = 31%
	20	40	800		(av. distance)
	150	30	4,500		$\frac{232}{4}$ = 58 ft
Swamping	35	50	1,750		
	27	40	1,080		
	232		8,130		(wt. damage)
					$\frac{8,130}{232}$ = 35%
				Area (ft^2)	
	20	90	1,800	60	(av. distance)
	18	90	1,620	72	$\frac{125}{5}$ = 25 ft
	35	60	2,100	105	
	32	80	2,560	128	(wt. damage)
Streambank	20	80	1,600	80	$\frac{9,680}{125}$ = 77%
erosion	125		9,680	445	
					(av. area)
					$\frac{445}{5}$ = 89 ft^2
					(av. depth)
					$\frac{445}{125}$ = 3.6 ft
	0	0	0		(av. distance)
	0	0	0		$\frac{36}{5}$ = 7.2 ft
	0	0	0		
Scour	10	60	600		
	26	60	1,560		(wt. damage)
	36		2,160		$\frac{2,160}{36}$ = 60%
				Area (ft^2)	
	0	0		0	(av. depth)
	0	0		0	$\frac{82}{36}$ = 2.3 ft
Scour	0	0		0	
depth	10	[1]3		30	
	26	[1]2		52	(av. cross sec.)
	36	[1]5		82	$\frac{82}{5}$ = 16.4 ft^2

[1]Depth in feet.

Table 7-6.—Reach damage summary from range data
Reach A Summary
Mud Creek Watershed Survey

From station to station[1]		Range 1	Range 2	Range 3	Range 4	Range 5	Total	Average
Infertile deposits	Distance (ft)	250	210	260	210	180	1,110	222
	Damage (%)[2]	30	30	20	40	40		31
Swamping	Distance (ft)	20	150	0	35	27	232	46.4
	Damage (%)	40	30	0	50	40		35
Streambank erosion	Distance (ft)	20	18	35	32	20	125	25
	Damage (%)	90	90	60	80	80		77
	Average depth (ft)	3	4	3	4	4		3.6
	Net X-sectional area (ft^2)	60	72	105	128	80		89
Flood-plain scour	Distance (ft)	0	10	0	26	0	36	7.2
	Damage (%)	0	60	0	60	0		60
	Average depth (ft)	0	3	0	2	0		2.3
	X-sectional area (ft^2)	0	30	0	52	0		16.4
Valley trenching	Distance (ft)	—	—	—	—	—		—
	Damage (%)	—	—	—	—	—		—
	Average depth (ft)	—	—	—	—	—		—
	X-sectional area (ft^2)	—	—	—	—	—		—
Texture	Gravel (%)	0	0	0	0	0		—
	Sand (%)	80	95	95	95	95		—
	Fines (%)	20	5	5	5	5		—

[1]All measurements from left side of valley, looking downstream, unless otherwise noted.
[2]To nearest 10 percent.

Next, expand the computed damage to the entire area of the reach. If the area of the flood plain can be obtained from maps or aerial photographs, divide the area of the reach by the average range length to obtain a valley length factor in acres per foot of width. This figure multiplied by the average width damaged on the ranges is the area damaged in the reach. An example of how to tabulate the area damaged by infertile deposits follows.

1	2	3	4	5	6	7
Reach	Area of reach	Average range length	Valley length factor (Col. 2 ÷ Col. 3)	Average width damaged	Area damaged (Col. 4 × Col. 5)	Reach damage (Col. 6 × 100 ÷ Col. 2)
	Acres	*Feet*	*Acres/foot*	*Feet*	*Acres*	*Percent*
A	432	714	0.605	222	134	31

If the area of the reach is not known, measure the mileage of stream valley in each reach, using large-scale maps or field surveys. Then determine the acreage of flood plain damage to date by the type of damage in each reach from the following equation:

$$a = 0.121bc \tag{7-10}$$

where

a = area damaged to date, acres
b = linear distance damaged on the average range, feet
c = length of stream valley in this reach, miles
0.121 = a conversion factor

$$\left(\frac{5{,}280 \text{ ft/mi}}{43{,}560 \text{ ft}^2\text{/acre}}\right)$$

The following example shows how damage data obtained by this procedure can be tabulated by reach.

1	2	3	4	5	6	7
Reach	Valley length (c)	0.121(c) (0.121 × Col. 2)	Average width damaged (b)	Area damaged (a) (Col. 3 × Col. 4)	Area of reach	Damage
	Miles	*Acres/foot*	*Feet*	*Acres*	*Acres*	*Percent*
A	5	0.605	222	134	432	31

The present condition of the flood plain can be determined by these methods. It is important that the physical data be complete and usable by an economist.

Deposition and Scour Damages

Damage figures provided to an economist for monetary evaluation should be reduced to average annual values. To project the future rate of damage from the historical average annual rate of damage, first determine whether the present rate of damage is in equilibrium, is increasing, or is decreasing. Also supply this information to the economist so that he or she can properly estimate future damages with and without installation of the project. Also work closely with the agronomist and soil scientist in determining physical damages from loss of productivity.

Equilibrium Damages

New damage by deposition or scour occurring each year can be offset by recovery of old damaged areas. Where such a condition exists, the benefits to be derived are the result of a reduced annual damage rate that shifts the equilibrium point in the direction of less income lost. Determine the total area damaged and the loss of productivity and estimate the amount of damaged area that could be expected to recover under flood-free conditions.

Increasing Damages

Damage may be increasing in extent or severity or both. In such a case, provide the economist with an estimate of the present damage rate, the rate at which the damage is increasing, and the eventual limits of the damage.

Decreasing Damages

Damaged areas may be recovering under present conditions; the damage can decrease in extent or in severity. If so, provide the economist with an estimate of the present damage rate, the rate at which the damage is decreasing, and the acreage that will be subject to damage after the limits of such decrease are reached.

Channel Erosion Damages

One method of reducing the total observed channel erosion to an average annual value is to compare the observed amount recorded on the field sheets with the average annual value determined by surveys or by aerial photographs made on different dates.

Since earlier flood-plain cross sections from engineering surveys are seldom available, it is more convenient to use aerial photographs made on different dates. Locate the control points common to each set of photos and carefully measure the change in position of the eroding bank in relation to these fixed points. Many measurements are necessary. Reduce the average distance of channel bank movement between photograph dates to an average annual value by dividing the distance by the number of years between photographs.

This value is usually suitable for estimating the rate of land loss and land depreciation from streambank erosion. Adjustments must be made, however, for serious valley trenching where, during the economic evaluation period, the headcut will advance into topographically or geologically different materials or the drainage above the advancing headcut will become significantly reduced. Make these adjustments according to established procedures.

To determine damage from lateral movement of channels, measure the actual area eroded or voided and depreciate it. The future damage may have little relation to the past damage even though the physical rate may be the same. For example, a valley trench in the past has progressed through relatively low-value land, but the advancing headcut in the future may engulf more valuable property, such as farmsteads, bridges, and orchards in its path. Thus, the direction of channel erosion as well as the rate becomes important in evaluating damage from channel erosion.

In computing physical damage by channel erosion, determine the annual rate at which land acreage is actually eroded or voided and provide this information to the economist. Work closely with the economist to determine the acreage to be depreciated. Consider the effects of channel erosion on tillage operations, ground levels, and isolation of farm fields, as well as other damages that can be evaluated.

Swamping Damages

Provide the economist with data concerning two phases of swamping damage.

Treat the first phase, which is the progressive swamping of flood-plain land now unswamped, as an incremental or increasing damage. Establish a rate of swamping, in acres per year, by dividing the acreage now swamped (determined from the flood-plain survey) by the length of time (usually determined by local interview) required to create the damage. Benefits will accrue to now unswamped flood plain through the elimination of reduction of this rate by project measures. Therefore, it must be known that some of the flood plain is still subject to progressive swamping. In no instance may the product of the rate of swamping and the evaluation period (in years) exceed the remaining area subject to such damage.

The second phase concerns the flood plain already damaged by swamping. In many places this land has also received deposits that will influence both the rate and capability of its recovery. The recovery of the land already swamped, after proper consideration of the influence of the deposition, is termed a swamping damage reduction.

Furnish the following items to the economist for use in evaluating swamping damages and swamping-damage-reduction benefits:

1. Rate and intensity (in percent or degree) of progressive swamping.
2. Area of unswamped flood plain subject to progressive swamping.
3. Area of flood-plain land already swamped.
4. Damage to land already swamped (in percent).
5. Estimated recovery period (in years) for land already swamped.
6. Estimated damage (in percent) remaining after recovery of swamped land.

Summarize all information developed from the flood-plain survey in tabular form as shown in table 7–7.

Table 7–7.—Summary of flood-plain damage, Reach A

Type of damage	Average length of range damaged	Area	Damage	Recovery period	Damage remaining after recovery
	Feet	*Acres*	*Percent*	*Years*	*Percent*
Infertile deposits	222	134	31	10	0
Swamping	46.4	26.9	37	15	10
Streambank erosion	25	15	77	0	—
Scour	7.2	4.4	60	0	—
Valley trenching	—	—	—	—	—

References

Eakin, H.M. 1939. Silting of reservoirs, revised by C.B. Brown. U.S. Dep. Agric. Tech. Bull. 524, 168 p.

Gottschalk, L.C. 1952. Measurement of sedimentation in small reservoirs. Trans. Am. Soc. Civ. Eng. 117:59–71.

Heinemann, H.G. 1963. Using the gamma probe to determine the volume-weight of reservoir sediment. Internat. Assoc. Sci. Hydrol., Symp. on Land Erosion, Bari, Italy, p. 410–423.

Heinemann, H.G., and V.I. Dvorak. 1965. Improved volumetric survey and computation procedures for small reservoirs. Fed. Inter-Agency Sediment. Conf. 1963 Proc. U.S. Dept. Agric. Misc. Publ. 970, p. 845–856.

Soil Conservation Service, U.S. Department of Agriculture. 1966. Procedure for determining rates of land damage, land depreciation, and volume of sediment produced by gully erosion. Engineering Division Tech. Release No. 32, Geology.

Soil Conservation Service, U.S. Department of Agriculture. 1979. Engineering layout, notes, staking, and calculations. Engineering Division Tech. Release No. 62.

U.S. Geological Survey, U.S. Department of the Interior. 1979. Index to water-data acquisition. Office of Water Data Coordination, Reston, Va.

U.S. Weather Bureau, U.S. Department of Commerce. 1961. Rainfall frequency atlas of the United States. Tech. Pap. No. 40.

United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Chapter 8

Sediment-Storage Design Criteria

Contents

	Page
General	8-1
Sediment yield	8-1
Sediment delivery ratio and gross erosion	8-1
Reservoir sedimentation surveys	8-3
Suspended-load records	8-3
Direct predictive equations	8-3
Sediment deposition	8-4
Trap efficiency	8-4
Design life	8-4
Distribution of sediment	8-5
Sediment storage requirements	8-6
Capacity requirements for sediment	8-6
Sediment storage allocation	8-6
Single-purpose floodwater-retarding reservoirs	8-7
Multiple-purpose reservoirs	8-7
Other procedures	8-7
Completing Form SCS–ENG–309	8-8
Heading	8-8
Sediment yield by sources (average annual)	8-8
Gross erosion and sediment delivery ratios	8-8
Data from reservoir sedimentation surveys	8-9
Data from suspended-load records	8-9
Data developed by direct predictive equations	8-9
Texture and volume-weight	8-9
Deposition	8-9
Sediment delivered to site (tons/yr)	8-9
Trap efficiency	8-9
Annual deposition (tons)	8-10
Design period (yrs)	8-10
Period deposition (tons)	8-10
Sediment passing (tons)	8-10
Examples	8-11
Sediment storage requirements	8-13
Condition of sediment	8-13
Percent of total	8-13
Deposition (tons)	8-13
Volume-weight (tons/acre-foot)	8-13
Storage required	8-13
Storage allocation	8-13
Examples	8-14
Computer processing	8-16
References	8-17
Appendix	8-18

Figures

	Page
8–1. Summary sheet for reservoir sedimentation design	8-2
8–2. Trap efficiency of reservoirs	8-5

Tables

	Page
8–1. Volume-weight of sediment by grain size	8-6

Chapter 8 Sediment-Storage Design Criteria

General

For a reservoir to be fully effective, its capacity must be large enough to offset depletion by sediment accumulation during the reservoir's design life. This chapter describes the principles and procedures for designing sediment storage in reservoirs proposed for SCS watershed or other program work plans.

Form SCS–ENG–309, Reservoir Sedimentation Design Summary (fig. 8–1), has been prepared to facilitate recording and computing the data needed for design. Examples of how to complete this form are presented for several types of reservoirs. Methods and procedures referred to but not included in this chapter are to conform to national procedures or to procedures approved by the national technical center (NTC) sedimentation geologist.

Form SCS–ENG–309 should be completed by a geologist familiar with sedimentation processes. When the form is properly filled out, the design criteria for sediment storage have been met. A copy of the completed form should be filed with other design information for each reservoir. The data then are available for use in the final design of reservoirs proposed for SCS work.

Sediment Yield

The several methods of determining sediment yield or rate of sediment accumulation in reservoirs are discussed in Chapter 6.

Sediment Delivery Ratio and Gross Erosion

The method most often used in SCS work, especially in the more humid areas of the country, is to determine sediment yield from the gross (total) erosion and the sediment delivery ratio. It works well for estimating current sediment yield and predicting the effects of land treatment and other measures on future sediment yield.

Procedures for determining quantitative values for each type of erosion are outlined in Chapter 3. The sediment delivery ratio (ratio of sediment yield to gross erosion) is estimated from the relationships discussed in Chapter 6. The product of gross erosion and the sediment delivery ratio is the sediment yield used in computing the design requirements.

SCS-ENG-309
REV. 8-74

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

RESERVOIR SEDIMENTATION DESIGN SUMMARY

WATERSHED ______________ SITE NO. ______ DRAINAGE AREA ______ Sq. Mi. ______ Acres

LOCATION ______________ STATE ______ PURPOSE ______________

DATA COMPUTED BY ______________________________ DATE ________

SEDIMENT YIELD BY SOURCES (AVERAGE ANNUAL)

		PRESENT CONDITIONS			FUTURE (AFTER CONS. TREATMENT)			
		ACRES	SOIL LOSS (TONS/AC)	TOTAL (TONS)	ACRES	SOIL LOSS (TONS/AC)	TOTAL (TONS)	
SHEET EROSION	CULTIVATED LAND							
SHEET EROSION	IDLE LAND							
SHEET EROSION	PASTURE - RANGE							
SHEET EROSION	WOODLAND							
SHEET EROSION								
		DELIVERY RATIO (%)		TONS DELIVERED	DELIVERY RATIO (%)		TONS DELIVERED	
SHEET EROSION - TOTAL								
GULLY EROSION								
STREAMBANK EROSION								
FLOODPLAIN SCOUR								
CONSTRUCTION								
			TOTAL			TOTAL		

DEPOSITION

TEXTURE INCOMING SEDIMENT		
% CLAY	% SILT	% COARSE
VOLUME WEIGHT DEPOSITED SEDIMENT LBS/CU. FT.		
SUBMERGED		
AERATED		

SEDIMENT DELIVERED TO SITE (TONS/YR)		TRAP EFFICIENCY (%)	ANNUAL DEPOSITION (TONS)	DESIGN PERIOD (YRS)	PERIOD DEPOSITION (TONS)	SEDIMENT PASSING (TONS)
PRESENT						
FUTURE						
FUTURE						
			TOTALS			

SEDIMENT STORAGE REQUIREMENTS

CONDITION OF SEDIMENT	% OF TOTAL	DEPOSITION (TONS)	VOLUME WEIGHT	STORAGE REQUIRED		STORAGE ALLOCATION (ACRE FEET)		
			TONS/AC.FT.	ACRE-FEET	WATERSHED INCHES	SEDIMENT POOL	RETARDING POOL	OTHER
SUBMERGED								
AERATED								
	TOTALS							

Figure 8-1.—Summary sheet for reservoir sedimentation design.

Reservoir Sedimentation Surveys

Reservoir sedimentation surveys are excellent sources of data for establishing sediment yield to reservoirs (see Chapter 6, Measured Sediment Accumulation).

Results of available sedimentation surveys should be reviewed for design purposes. Miscellaneous Publication No. 1362 (Agricultural Research Service 1978) provides data obtained from many reservoir surveys. Information about the rates of sediment deposition in reservoirs typical of the area under consideration can be obtained from this publication. If no such information is available, it could be helpful to make sedimentation surveys of any reservoirs in the area. It is important that the sedimentation record for reservoirs surveyed or scheduled for survey be long enough to ensure that the data represent average conditions. It is also important to know the history of reservoirs considered for sedimentation surveys. Removal or drying of sediment and changes in spillway elevation affect volume and distribution of sediment.

In mountainous areas differences in sediment yield rates are often inconsistent with differences in size of drainage area. Also, if channel-type erosion increases downstream (for example, from main stem channel-bank cutting), the sediment yield rate may increase with increasing size of drainage area. Therefore, judgment must be used in establishing the relationship between sediment yield and size of drainage area.

Suspended-Load Records

Time seldom is available to establish a suspended-load station at a proposed site and obtain enough data before design information is required. If suspended-load records are available from nearby locations representative of the areas for which the information is required, however, these data can be useful (see p. 6–6).

Direct Predictive Equations

Predictive equations based on watershed and reservoir characteristics have been developed in some areas to estimate sediment yield or sediment accumulation in reservoirs. Such equations must be restricted to the specific area they represent.

The amount of sediment accumulation in a reservoir depends on the sediment yield to the reservoir and the trap efficiency. How the accumulated sediment is distributed within the reservoir depends on the character of the inflowing sediment, the operation of the reservoir, and other factors.

Trap Efficiency

Trap efficiency is the amount (percentage) of the sediment delivered to a reservoir that remains in it. It is a function of detention storage time, character of the sediment, nature of the inflow, and other factors. Trap efficiency can be readily estimated on the basis of the ratio of the capacity of the reservoir to the average annual inflow (Brune 1953, Gottschalk 1965) by using the following procedure:

1. Estimate the total capacity required of the reservoir in watershed inches (see page 8–13), including the total capacity allocated to floodwater detention, sediment storage, and other uses. Since an actual value cannot be obtained until final design is completed, estimate the total capacity as follows:
   a. Assume, for the particular physiographic area, a reasonable sediment-storage volume that might be required for the design life of the structure; e.g., 1.5 in.
   b. Obtain from the hydrologist an estimate of the required floodwater-detention storage; e.g., 4.5 in.
   c. Add the values for 1a and 1b to get an estimate of the total capacity of the reservoir; i.e., $1.5 + 4.5 = 6.0$ in. Include any additional storage for water supply, recreation, and other uses in the total. If an estimate of the total required storage in acre-feet is available, convert this value to watershed inches to simplify the calculation.
2. Determine the average annual runoff in inches. This value can be determined from the hydrologic analysis of the watershed, from Hydrologic Investigation Atlas HA–212 (Busby 1966) or from other available information. In this example, the average annual runoff is 17.5 in.
3. Divide the aproximate total capacity in inches (item 1c) by the average annual runoff in inches (item 2) to obtain the capacity-inflow ratio (C/I); i.e., $C/I = 6.0 \div 17.5 = 0.343$.
4. Obtain the trap efficiency for a given C/I fro the vertical scale of figure 8–2. To do so, estimate the texture of the incoming sediment on the basis of the character of watershed soils and the principal sediment sources. If the incoming sediment is predominantly bedload or coarse material or is highly flocculated, use the upper curve of figure 8–2 to determine trap efficiency. If the incoming sediment is primarily colloids, dispersed clays, and fine silts, use the lower curve. If the incoming sediment consists of various grain sizes widely distributed, use the median curve. The texure also affects the distribution and allocation of the sediment in various pools.

The curves in figure 8–2 cannot be applied directly to dry reservoirs. If water flows through ungated outlets below the crest of the principal spillway, trap efficiency is likely to be lowered. If the inflowing sediment is predominantly sand, reduce the trap efficiency by about 5 percent; if the sediment is chiefly fine textured, reduce the trap efficiency by about 10 percent.

If the incoming sediment is composed essentially of equal parts of clay, silt, and fine sand and the proposed structure is to have a submerged sediment pool, use the median curve of figure 8–2 without adjustment. In the example ($C/I = 0.343$) trap efficiency would be 95 percent. In a situation similar except that the structure is designed as a dry reservoir, trap efficiency would be 85 percent.

Design Life

The design life of a reservoir is the period required for the reservoir to fulfill its intended purpose. Structures designed by SCS in the watershed protection and flood prevention programs usually are designed for a life of 50 or 100 years. Provision must be made to ensure the full design storage capacity for the planned design life. This may mean cleaning out deposited sediment at predetermined intervals during the design life or, as is generally the situation, providing enough capacity to store all the accumulated sediment for the reservoir's design life without dimininshing the design water storage.

Land treatment (conservation) measures seldom are fully effective in reducing erosion and sediment yield in less than 5 years. Often a longer time is required. This delay in effectiveness during the

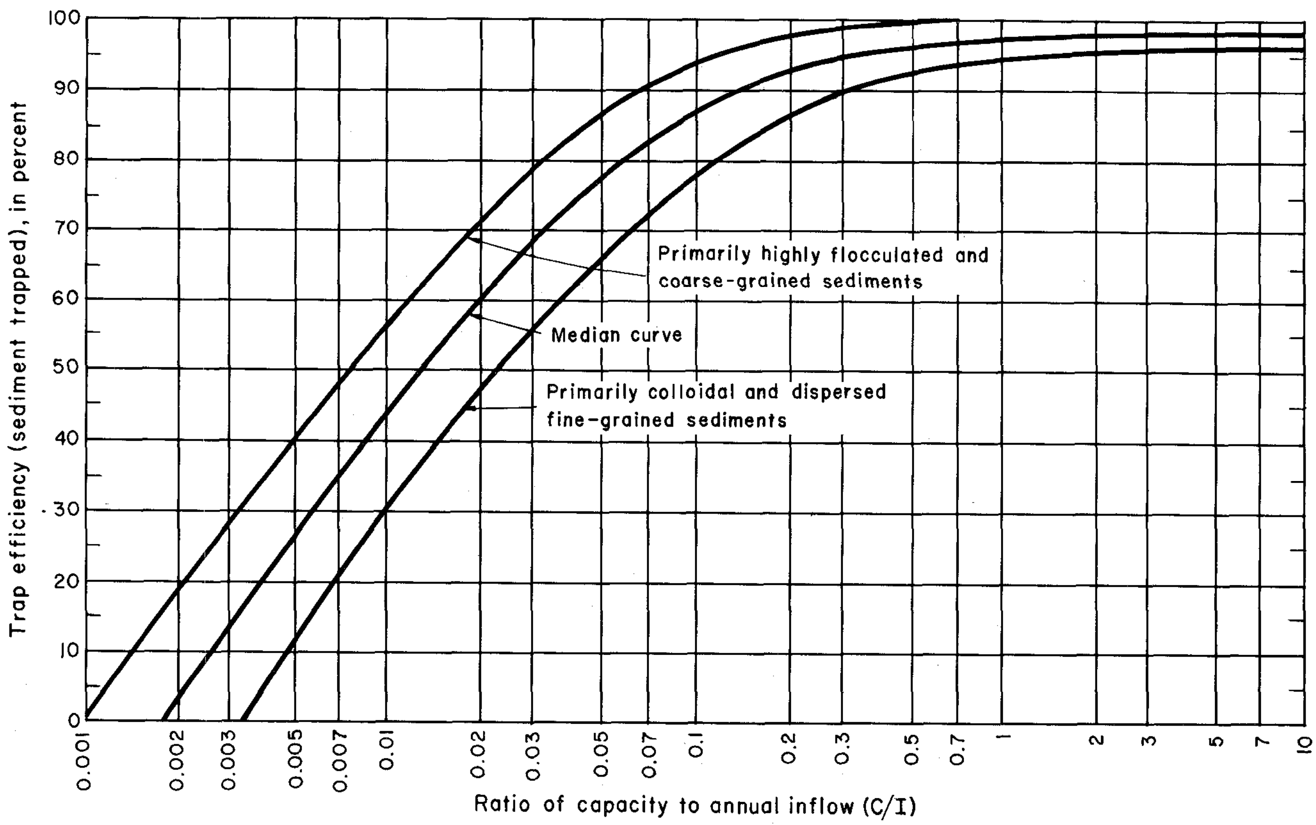


Figure 8–2.—Trap efficiency of reservoirs.

early part of a reservoir's life (Present Conditions on SCS–ENG–309) must be recognized in design. Determine, in consultation with the state program staff and the area and district conservationists, how many years will be required for the proposed land-treatment measures to be installed and become effective.

Distribution of Sediment

The total storage capacity of a reservoir must include capacity for all water storage plus capacity for the sediment expected to accumulate during the reservoir's design life. Consequently, the amount of sediment that will be deposited above the elevation designated for the sediment pool must be estimated. Such deposits may materially affect the proper functioning of the structure.

The amount of sediment that will be deposited above the principal spillway varies with the nature of the sediment, shape of the reservoir, topography of the reservoir floor, nature of the approach channel, detention time, and purpose of the reserovir. The coarse sediment settles quickly as the velocity of the water decreases. Generally, sediment inflow is greatest when detention capacity is being used and some sediment is deposited at elevations above the principal spillway. Usually, more coarse material than fine material is deposited above this elevation. The texture of the incoming sediment is the basis for estimating the percentage of incoming sediment that will be deposited above the elevation of the principal spillway. Use the following guidelines for estimating this percentage.

1. For watersheds of low to moderate relief in which the predominant sources of sediment are silty and clayey soils, sheet flow is the principal eroding agent, and the sediment is transported primarily in suspension: 10 percent.
2. For watersheds of low to moderate relief in which the incoming sediment consists of nearly equal amounts of medium to fine sands, silts, and clays; sheet flow and channel erosion are the principal agents; and the coarser material is

transported along the bed and the fine materials are transported in suspension: 20 percent.

3. For watersheds of moderately high relief in which channel-type erosion is the primary source of sediment, coarse sands and gravel transported as bedload make up a large part of the incoming sediment, and smaller amounts of fine-grained sediment are transported in suspension: 30 percent.

4. For watersheds of high relief in which the primary sediment load consists of boulders, cobbles, and sand: more than 30 percent.

Adjust these percentages upward or downward according to local watershed and reservoir conditions.

Capacity Requirements for Sediment

The incoming sediment that is deposited under water is called submerged sediment. The sediment deposited above the elevation of the principal spillway is subject to alternate wetting and drying and is called aerated sediment. Submerged sediment is the sediment in the sediment pool and aerated sediment is the sediment in the retarding pool in all single-purpose floodwater-retarding structures except dry reservoirs. In dry reservoirs all sediment is considered aerated.

The distinction between submerged sediment and aerated sediment is important in determining the capacity that each will displace. The volume occupied by the deposited sediment depends on its texture and whether it is submerged or aerated. If field measurements are not available, use table 8–1 as a guide to estimating the volume-weight of sediment in pounds per cubic foot.

Estimate the volume-weight of each kind of sediment according to whether it is submerged or aerated. Any sediment volume determined on the basis of aerated volume-weight retains that same volume even though the sediment may be submerged later.

Table 8–1.—Volume-weight of sediment by grain size

Grain size	Volume-weight of sediment	
	Submerged	Aerated
	lb/ft³	*lb/ft³*
Clay	35–55	55–75
Silt	55–75	75–85
Clay-silt mixtures (equal parts)	40–65	65–85
Sand-silt mixtures (equal parts)	75–95	95–110
Clay-silt-sand mixtures (equal parts)	50–80	80–100
Sand	85–100	85–100
Gravel	85–125	85–125
Poorly sorted sand and gravel	95–130	95–130

Sediment Storage Allocation

The required sediment storage must be allocated among the various reservoir pools. Certain design elevations and flood-routing procedures depend on the expected distribution of the sediment within the reservoir. Keep the following definitions in mind in making the allocations. *Sediment storage* is the volume allocated to the total accumulation of sediment. The *sediment pool* is the reservoir space allocated to the accumulation of submerged sediment during the design life of the structure. The *sediment pool elevation* is the elevation (on the stage-storage curve) corresponding to the expected volume of submerged sediment.

The following general guidelines will help in allocating the sediment storage in several situations. These guidelines are primarily for reservoirs in which most of the sediment is submerged. For structures designed as dry reservoirs, the same guidelines apply except that all the sediment is aerated.

Single-Purpose Floodwater-Retarding Reservoirs

Single-stage principal spillway.—The sediment-pool elevation is the crest elevation of the principal spillway. Since water is expected to fill this space until it is displaced by sediment, compute this sediment volume by using the submerged volume-weight. Compute the volume of the sediment expected in the retarding pool by using the aerated volume-weight.

Two-stage principal spillway.—The sediment-pool elevation is the elevation of the low-stage inlet of a two-stage principal spillway. Since water is expected to fill this space until it is displaced by sediment, compute this sediment volume by using the submerged volume-weight.

Some sediment is deposited between the elevations of the low-stage and high-stage inlets. Compute this sediment volume by using the aerated volume-weight. Compute the sediment volume expected in the retarding pool by using the aerated volume-weight.

Multiple-Purpose Reservoirs

The sediment pool volume in multiple-purpose reservoirs will be based on submerged volume-weight. Add the volume of beneficial water storage to that of the submerged sediment. Compute the sediment volume that will be deposited above the elevation of the principal spillway by using the aerated volume-weight.

Multiple-purpose structures can be designed with either a single-stage or a two-stage principal spillway. If a two-stage principal spillway is used, the sediment deposited between the elevations of the low- and high-stage inlets must be considered as well as that deposited above the elevation of the high-stage inlet. Compute the volume of this sediment by using the aerated volume-weight.

Other Procedures

Any procedures for allocating sediment storage capacity not specifically covered in this chapter should be developed in consultation with the st of the national technical centers (NTC's).

Certain background information is necessary for every reservoir being designed. Indicate the location of the structure on an aerial photograph, a U.S. Geological Survey quadrangle, or other suitable map so that the watershed, including any problem areas above the site, can be delineated and measured. Estimate the total reservoir capacity required for all purposes. Several major parts of Form SCS–ENG–309 are considered in the following paragraphs.

Heading

State the purpose of the reservoir as in these examples: single-purpose—flood prevention; multiple-purpose—flood prevention and water supply. Note any other pertinent information about the structure, such as single or two-stage riser, in the space to the left and below the heading. The rest of the information required in the heading is self-explanatory. A completed heading is shown in example 1.

Sediment Yield by Sources (Average Annual)

Gross Erosion and Sediment Delivery Ratios

Form SCS–ENG–309 was designed to show the relationship of gross erosion and sediment delivery ratios to sediment yield (see Chap. 6). Use this part of the form to record estimates of the erosion occurring in the drainage area of the reservoir and the sediment delivery ratios. Estimates of the annual amounts of erosion must be realistic and reasonable, for both "Present Conditions" and "Future (After Conservation Treatment)." Usually, these estimates are made by delineating problem areas in the drainage area and computing sheet erosion and other components of the total erosion individually. Separate worksheets are generally used for this purpose; therefore, enter only totals for each erosion component on the form. It is preferable, however, to show the acreage and rate of soil loss for each land use listed under "Sheet Erosion." Compute the "Soil Loss (tons/acre)" for sheet erosion according to the procedures in Chapter 3, using the guides and releases prepared by the NTC staffs. The basic information required for this computation can be obtained from soil survey data available in field offices or from supplementary investigations.

Compute the "Future (After Conservation Treatment)" estimates from the most realistic information available. Predictions of reductions in erosion rates from the various sediment sources should reflect the land treatment data provided by the district conservationist. These future reductions must be realistic.

Estimate the total amount of material eroded by channel-type processes (gullies, streambanks, etc.) for both present and future conditions on the basis of a field reconnaissance or detailed study with aerial photographs and soil survey data. The volume of sediment produced by gullying can be determined by the procedure given in Technical Release No. 32 (Soil Conservation Service 1966) or by those given in Chapter 3. Information concerning streambank erosion and flood-plain scour can be obtained from the flood-plain damage survey. If the streambed is degrading and is a source of sediment, plan the procedures for determining the annual amount of streambed erosion in consultation with the staff of the appropriate NTC. Enter the total amount of material eroded by channel-type

SCS-ENG-309
REV. 8-74

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

RESERVOIR SEDIMENTATION DESIGN SUMMARY

WATERSHED Wett Creek SITE NO. 7 DRAINAGE AREA 3.44 Sq. Mi. 2,200 Acres

LOCATION 42°50'10",87°07'30"W STATE MY PURPOSE Single Purpose - FP

DATA COMPUTED BY A. Competent, Geologist DATE 7/4/82

Example 1.

obtain the erosion information with Form SCS–ENG–309 as supporting data.

See "Channel Erosion: Factors Involved" in Chapter 3 for information on estimating long-term streambank erosion.

Construction sites and strip-mine areas can be major sources of sediment. The effectiveness of erosion control measures must be evaluated realistically in estimating sediment yield from these areas.

In evaluating any probable construction during the project life, do not underestimate highway construction. During a 100-year project life, most highways will be rebuilt and major relocations and new construction are likely.

To complete this part of the form, estimate the sediment delivery ratios and the sediment yield to the structure site. For each erosion component, estimate the percentage of eroded material that reaches the site. Various guides for estimating sediment delivery ratios in terms of watershed characteristics have been prepared by the NTC's. Consult these guides, as well as those listed in Chapter 6, to obtain values to enter on the form. Each entry under "Tons Delivered" is the product of the total soil loss for one erosion component and the corresponding "Delivery Ratio (%)." Add the entries under "Tons Delivered" to get the sediment yields for "Present" and "Future" conditions.

If upstream structures control sediment, add the sediment passing these structures to the sediment yield (determined by the foregoing procedure) for the net uncontrolled drainage area. The expected effective life of the upstream structures (e.g., debris basins) must be considered.

Data from Reservoir Sedimentation Surveys

If the sediment yield rate determined from reservoir sedimentation surveys is used, enter the values as the total "Tons Delivered."

State on the form that sedimentation surveys were used to develop the values. Identify the source of the data and file all worksheets with the form.

Data from Suspended-Load Records

Enter sediment yield information obtained from suspended-load records in the same manner as information obtained from reservoir sedimentation surveys. State on the form that suspended-load records were used. File the supporting data, including identification of the stations used, with the form.

Data Developed by Direct Predictive Equations

If a predictive equation is used to determine sediment yield, enter the computed sediment yield in the appropriate spaces for total "Tons Delivered." Note the equation used on the form, and file the worksheets with the form.

A completed section "Sediment Yield by Sources (Average Annual)" is shown in example 2.

If future land use includes developments such as urbanization or strip mining, it may be necessary to subdivide "future" conditions to delineate the land-use changes. This can be done on Form SCS–ENG–309 by completing only the heading and sediment yield section on one form and then continuing on a second form. See example 3.

Texture and Volume-Weight

Enter the estimated texture of the incoming sediment in the spaces provided. Determine the volume-weight (pounds per cubic foot) for submerged and aerated sediment on the basis of the data from measured reservoir sediment samples or the estimated texture, using guidelines presented in table 8–1. Enter these values in the appropriate spaces.

Deposition

Use this section to compute the amount of sediment that will be deposited in the reservoir.

Sediment Delivered to Site (Tons/Yr)

Enter the sediment yield values (the total tons delivered) in the appropriate "Present" and "Future" spaces.

To allow for gradual improvement of watershed conditions during the installation period of land treatment measures and the period during which these measures become effective in reducing erosion, use an average of the calculated present and future rates of sediment yield for the "Present" value.

Trap Efficiency

Estimate trap efficiency on the basis of the discussions on page 8–4. Data now available are not sufficient to predict how increasing age of a reservoir affects trap efficiency. Use the same value for the trap efficiency of a given reservoir under both "Present" and "Future" conditions.

Annual Deposition (Tons)

"Annual Deposition (Tons)" is the product of "Sediment Delivered to Site (Tons/Yr)" and "Trap Efficiency (%)" for each line.

Design Period (Yrs)

The design period for "Present" conditions is the expected number of years required for the proposed land treatment measures to be installed and to become fully effective in reducing erosion and sediment yield.

Period Deposition (Tons)

"Period Deposition" is the product of "Annual Deposition" and the number of years in each design period. The sum of the "Period Deposition" values entered in the "Total" space of the "Period Deposition" column, represents the total amount of sediment, in tons, that will be deposited in the reservoir during the design life of the structure.

Sediment Passing (Tons)

"Sediment Passing" is the product of the sediment delivered to the site (tons/yr) and the number of years in the design period minus the deposition in the design period. Use the result as a basis for reporting the effects of structures on downstream sedimentation, for environmental impact statements, and for estimates of the reduction in sediment damage.

SEDIMENT YIELD BY SOURCES (AVERAGE ANNUAL)

		PRESENT CONDITIONS			FUTURE (AFTER CONS. TREATMENT)		
		ACRES	SOIL LOSS (TONS/AC)	TOTAL (TONS)	ACRES	SOIL LOSS (TONS/AC)	TOTAL (TONS)
SHEET EROSION	CULTIVATED LAND 1/	540	18.5	2/ 9,990	500	12.9	2/ 6,450
	IDLE LAND	150	8.1	1,215			
	PASTURE - RANGE	880	4.1	3,610	950	2.9	2,755
	WOODLAND	630	2.3	1,450	750	1.5	1,125

	DELIVERY RATIO (%)		TONS DELIVERED	DELIVERY RATIO (%)		TONS DELIVERED
SHEET EROSION - TOTAL	20	16,265	2/ 3,255	20	10,330	2/ 2,065
GULLY EROSION	80	6,600	5,280	80	3,160	2,530
STREAMBANK EROSION	90	1,200	1,080	90	1,200	1,080
FLOODPLAIN SCOUR						
CONSTRUCTION	50	2,000	1,000	50	800	400
		TOTAL	3/ 10,615		TOTAL	4/ 6,075

[1]Includes row crops, small grains, meadow.
[2]Product of proceding two columns rounded to nearest 5 tons.
[3]Enter under "Sediment Delivered to Site" in "Present" space of "Deposition" section.
[4]Enter under "Sediment Delivered to Site" in "Future" space of "Deposition" section.

Example 2.

SCS-ENG-309
REV. 8-74

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

RESERVOIR SEDIMENTATION DESIGN SUMMARY

WATERSHED Wett Creek SITE NO. 7 DRAINAGE AREA 3.44 Sq. Mi. 2,200 Acres

LOCATION ______ STATE ______ ~~PURPOSE~~ Page 2 of 2

DATA COMPUTED BY A. Competent DATE 7/4/82

SEDIMENT YIELD BY SOURCES (AVERAGE ANNUAL)

		PRESENT CONDITIONS			FUTURE (AFTER CONS. TREATMENT)		
		ACRES	SOIL LOSS (TONS/AC)	TOTAL (TONS)	ACRES	SOIL LOSS (TONS/AC)	TOTAL (TONS)
SHEET EROSION	CULTIVATED LAND				400	11.7	4,680
	IDLE LAND						
	PASTURE - RANGE				950	2.9	2,755
	WOODLAND				750	1.5	1,125
					100		

	PRESENT CONDITIONS			FUTURE (AFTER CONS. TREATMENT)		
	DELIVERY RATIO (%)		TONS DELIVERED	DELIVERY RATIO (%)		TONS DELIVERED
SHEET EROSION - TOTAL				20	8,560	1,710
GULLY EROSION				80	1,500	1,200
STREAMBANK EROSION				90	1,000	900
FLOODPLAIN SCOUR						
CONSTRUCTION				50	800	400
		TOTAL	xxx		TOTAL	4,210

Example 3.

As noted earlier, direct predictive equations can be used to determine sediment yields. Predictive equations are sometimes developed to estimate total deposition in a reservoir. Sediment yield, trap efficiency, and life of the reservoir usually are among the variables incorporated in these equations. If such an equation is used, enter only the estimated deposition and the sediment passing the site for the required time periods in the last two columns of this section.

Examples

Examples 4, 5, and 6 illustrate the use of this section of the form for several different situations.

DEPOSITION

TEXTURE INCOMING SEDIMENT [1]		
% CLAY	% SILT	% COARSE
30	40	30
VOLUME WEIGHT DEPOSITED SEDIMENT LBS/CU. FT.		
SUBMERGED	50	
AERATED	82	

	SEDIMENT DELIVERED TO SITE [2] (TONS/YR)	TRAP [3] EFFICIENCY (%)	ANNUAL [4] DEPOSITION (TONS)	DESIGN PERIOD (YRS) [5]	PERIOD DEPOSITION [6] (TONS)	SEDIMENT PASSING [7] (TONS)
PRESENT	10,615	95	10,085	8	80,680	4,240
FUTURE	6,075	95	5,770	42	242,340	12,810
FUTURE						
			TOTALS	50	323,020	17,050

[1]See page 8–9.
[2]Sediment yield entries.
[3]See page 8–9.
[4]Product of [2] and [3] to nearest 5 tons.
[5]See page 8–10.
[6]Product of [4] and [5].
[7]See page 8–10.

Example 4. 50-Year-Life Reservoir

DEPOSITION

TEXTURE INCOMING SEDIMENT		
% CLAY	% SILT	% COARSE
30	40	30
VOLUME WEIGHT DEPOSITED SEDIMENT LBS/CU. FT.		
SUBMERGED	50	
AERATED	82	

	SEDIMENT DELIVERED TO SITE [1] (TONS/YR)	TRAP EFFICIENCY (%)	ANNUAL DEPOSITION (TONS)	DESIGN PERIOD (YRS) [2]	PERIOD DEPOSITION (TONS)	SEDIMENT PASSING (TONS)
PRESENT	10,615	95	10,085	8	80,680	4,240
FUTURE	6,075	95	5,770	92	530,840	28,060
FUTURE						
			TOTALS	100	611,520	32,300

[1]Entries from "Sediment Yield."
[2]See page 8–10.

Example 5. 100-Year-Life Reservoir

DEPOSITION

TEXTURE INCOMING SEDIMENT		
% CLAY	% SILT	% COARSE
30	40	30
VOLUME WEIGHT DEPOSITED SEDIMENT LBS/CU. FT.		
SUBMERGED		50
AERATED		82

SEDIMENT DELIVERED TO SITE 1/ (TONS/YR)		TRAP EFFICIENCY (%)	ANNUAL DEPOSITION (TONS)	DESIGN PERIOD (YRS)2/	PERIOD DEPOSITION (TONS)	SEDIMENT PASSING (TONS)
PRESENT	10,615	95	10,085	8	80,680	4,240
FUTURE	6,075	95	5,770	42	242,340	12,810
FUTURE	4,210	95	4,000	50	200,000	10,500
			TOTALS	100	523,020	27,550

[1]Entries from "Sediment Yield."
[2]See page 8–10.

Example 6. 100-Year-Life Reservoir–Major Land-Use Changes Expected During Second 50-Year Period

Sediment Storage Requirements

Use this section to estimate total amount and distribution of sediment storage capacity in the various pools of the reservoir.

Condition of Sediment

This column provides headings indicating whether the sediment is expected to be submerged or aerated.

Percent of Total

Use this column to record estimated percentages of the incoming sediment deposited in submerged and aerated environments. The values used should conform with the guidelines previously discussed.

Deposition (Tons)

In this column enter the estimated amount of sediment deposited (tons) previously recorded in the "Deposition" part of the form. Enter the total "Period Deposition" in the "Total" space of this column.

Multiply the total "Deposition" by the percentages to determine how many tons of sediment will be submerged and how many aerated. Enter these values in the appropriate spaces of this column.

Volume-Weight (Tons/Acre-Foot)

The sediment deposited in the reservoir must be expressed in terms of the volume it will displace. Convert the volume-weights entered in the small box "Volume-Weight, Deposited Sediment (lbs/cu.ft.)" to tons per acre-foot by multiplying them by 21.78.

Enter the values derived for both submerged and aerated sediment in the corresponding spaces of this column.

Storage Required

Determine the acre-feet of storage required by dividing "Deposition (Tons)" by the corresponding "Volume-Weight (Tons/Ac. Ft.)" for both sediment conditions. The sum of the values in this column is the total capacity required in the reservoir for sediment storage.

Use the column "Watershed Inches" to express the acre-feet of sediment shown in column 5, in equivalent watershed inches. Determine these values by using the following equation:

$$\text{Watershed inches} = 0.01875 \left(\frac{\text{acre-ft of sediment storage}}{\text{drainage area in sq miles}}\right)$$

Storage Allocation

Allocate the required sediment storage among the various pools in the reservoir. Use the guidelines previously discussed.

If equations have been used to predict the total sediment accumulation expected in a reservoir during its design life, enter the results in the total "Storage Required" space. Storage allocations can be made from this value. These equations sometimes predict the distribution and allocation of the deposited sediment. If so, enter the predicted allocations in the appropriate spaces. Note the use of such equations on the form and file with the form any sheets used in the computation.

Examples

Examples 7, 8, and 9 illustrate how the "Sediment Storage Requirements" part of the form was completed for three different designs.

SEDIMENT STORAGE REQUIREMENTS

CONDITION OF SEDIMENT 1/	% OF TOTAL 1/	DEPOSITION (TONS) 2/	VOLUME-WEIGHT 3/	STORAGE REQUIRED 4/		STORAGE ALLOCATION 5/ (ACRE-FEET)		
			TONS/AC.FT.	ACRE-FEET	WATERSHED INCHES	SEDIMENT POOL	RETARDING POOL	OTHER
SUBMERGED	80	258,415	1,089	237.3	1.29	237.3		
AERATED	20	64,605	1,786	36.2	0.20		36.2	
	TOTALS	323,020		273.5	1.49	6/ 237.3	7/ 36.2	

[1]See discussion, page 8–13.
[2]See page 8–13.
[3]See page 8–13.
[4]See page 8–13.
[5]Guidelines given on page 8–13.
[6]This capacity establishes the crest elevation of the principal spillway.
[7]Add this capacity to the required floodwater-retarding volume to establish the elevation of the emergency spillway.

Example 7. Single-Purpose Floodwater-Retarding Reservoir, 50-Year Design Life, Single-Stage Principal Spillway

SEDIMENT STORAGE REQUIREMENTS

CONDITION OF SEDIMENT	% OF TOTAL	DEPOSITION (TONS)	VOLUME WEIGHT	STORAGE REQUIRED		STORAGE ALLOCATION (ACRE-FEET)		
			TONS/AC.FT.	ACRE-FEET	WATERSHED INCHES	SEDIMENT POOL	RETARDING POOL	OTHER 1/
SUBMERGED	80	489,215	1,089	449.2	2.45	449.2		
AERATED	20	122,305	1,786	68.5	0.37		20.6	47.9
	TOTALS	611,520		517.7	2.82	2/ 449.2	3/ 20.6	4/ 47.9

[1]Retarding pool between low- and high-stage inlets.
[2]Establishes crest elevation of low-stage inlet.
[3]Add this volume to required retarding capacity above the elevation of the high-stage inlet to determine the elevation of the emergency spillway.
[4]Add this volume to the required retarding capacity between the low- and high-stage inlets to determine the elevation of the high-stage inlet.

Example 8. Single-Purpose Floodwater-Retarding Reservoir, 100-Year Design Life, Two-Stage Principal Spillway, 70 percent of aerated sediment below high-stage inlet

SEDIMENT STORAGE REQUIREMENTS

CONDITION OF SEDIMENT	% OF TOTAL	DEPOSITION (TONS)	VOLUME WEIGHT	STORAGE REQUIRED		STORAGE ALLOCATION (ACRE-FEET)		
			TONS/AC.FT.	ACRE-FEET	WATERSHED INCHES	SEDIMENT POOL	RETARDING POOL	OTHER 1/
SUBMERGED	80	489,215	1,089	449.2	2.45	382.2		2/ 67.0
AERATED	20	122,305	1,786	68.5	0.37		68.5	
	TOTALS	611,520		517.7	2.82	3/ 382.2	68.5	4/ 67.0

[1]Beneficial water storage.

[2]Allocate the part of submerged sediment to the beneficial storage pool in consultation with the national technical center sedimentation geologist.

[3]Submerged sediment in sediment pool.

[4]Submerged sediment deposited in capacity for beneficial use.

Note: Add the required capacity for beneficial use to the sum of [3] and [4] to determine the crest elevation of the principal spillway.

Example 9. Multiple-Purpose Reservoir, 100-Year Design Life

Computer Processing

If detailed erosion computations are made by use of the Universal Soil Loss Equation and other procedures, Form SCS–ENG–309 provides space for summary values only. Attach the detailed data and computations documentation to the form. An alternative procedure is computer processing.

Computer processing has the following advantages over hand computations:

1. All data are recorded in a standard format on data input forms and on computer data listings.
2. Procedures and equations are standardized.
3. The computer printout is an acceptable substitute for the data and computation documentation and the completed Form SCS–ENG–309.
4. The geologist is freed from time-consuming routine computations.
5. Computations are less subject to error.

The Appendix illustrates data input, data listing, and printout for one of the examples previously discussed. Details on computer processing capabilities are available from the NTC sedimentation geologists.

References

Agricultural Research Service, U.S. Department of Agriculture. 1978. Sediment deposition in U.S. reservoirs. Summary of data reported through 1975. Misc. Publ. 1362.

Boyce, Robert C. 1975. Sediment routing with sediment delivery ratios. *In* Present and prospective technology for predicting sediment yields and sources. USDA Agric. Res. Serv. Publ. S–40.

Brune, Gunnar M. 1953. Trap efficiency of reservoirs. Am. Geophys. Union Trans. 34(3):407–417.

Busby, Mark W. 1966. Annual runoff in the conterminous United States. *In* U.S. Geol. Surv. Hydrol. Inv. Atlas HA–212.

Gottschalk, L.C. 1965. Trap efficiency of small floodwater-retarding structures. Am. Soc. Civ. Eng. Conf., Mar. 8–12. Mobile, Ala. Conf. Preprint 147.

Soil Conservation Service, U.S. Department of Agriculture. 1966. Procedure for determining rates of land damage, land depreciation, and volume of sediment produced by gully erosion. Engineering Division Tech. Release No. 32, Geology.

Soil Conservation Service, U.S. Department of Agriculture. 1975. Procedure, sediment storage requirements for reservoirs. Engineering Division Tech. Release No. 12.

SCS-ENG-309A
JANUARY 1975

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

GROSS EROSION AND SEDIMENT YIELD
WATERSHED TITLE SHEET

SHEET 1 OF 5

1 … 36 … 46 … 56 … 61 … 76 … 80

WATERSHED NAME AND STATE	TOTAL ACRES 1/	DESIGN LIFE OF PROJECT (YEARS)	NUMBER OF FINAL SUBWATERSHED 2/	CARD NO.
SEDIMENT STORAGE PROCEDURE - EXAMPLE	——	100.	01	1

BY (NAME AND TITLE)	DATE		CARD NO.
A. COMPETENT GEOLOGIST	07/04/82		2

GENERAL INSTRUCTIONS

Card Numbers to be in consecutive numerical order, beginning with 1.

100.	

Decimals are required for All numbers in "open" spaces.

	7		3

Do Not use decimals with numbers in "compartmented" spaces. Right justify numbers.

Cross out unused blanks of these forms.

INSTRUCTIONS FOR THIS FORM

1/ Insert 0. if watershed summary is Not desired.
2/ This number must be 50 or less.

SCS-ENG-309B
JANUARY 1975

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

GROSS EROSION AND SEDIMENT YIELD

SUBWATERSHED – GENERAL INFORMATION – DETAILED LAND USE

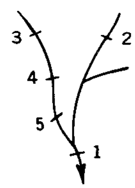
SHEET 2 OF 5

1 6 11 16 21 26 31 36 41 46 51 56 61 66 68 71 76 80

SITE NUMBER OR SUBWATERSHED DESIGNATION	PRESENT TRAP EFFI-CIENCY 1/	SUBWATERSHED DRAINAGE AREA (ACRES)	SHEET EROSION ACRES		SHEET EROSION DELIVERY RATIO %	UNIVER-SAL RAINFALL FACTOR R	YEARS OF SEDIMENT STORAGE 3/	SUBWATERSHED	
			SUBWATERSHED TOTAL	SAMPLE TOTAL 2/				NO. 4/	CARD NO.
WETT CREEK W/S SITE NO. 7	———	2200.	2200.	220.	20.	100.	100.	01	3

NUMBER OF TIME PERIODS 5/	LENGTH OF TIME PERIODS (YEARS)							NO. OF SITES IN RELATED GROUP 6/	LIST SUBWATERSHED NUMBERS OF SUBWATERSHEDS IN SERIES IMMEDIATELY UPSTREAM 7/ 8/	CARD NO.
	FIRST	SECOND	THIRD	FOURTH	FIFTH	SIXTH	SEVENTH			
2	8.	92.	—	—	—	—	—	—	—	4

1/ USE 0. IF PRESENT TRAPPING EFFECT IS ZERO. USE ACTUAL TRAP EFFICIENCY (AS WHOLE NUMBER PERCENT) IF THIS IS AN EXISTING LAKE OR SWAMP.
2/ IF "SAMPLE TOTAL" IS SAME AS "SUBWATERSHED TOTAL", DO NOT ENTER "SAMPLE TOTAL".
3/ USE 0. IF SEDIMENT STORAGE COMPUTATIONS ARE NOT DESIRED.
4/ THIS NUMBER MUST BE 50 OR LESS.
5/ IF "NUMBER OF TIME PERIODS" IS GREATER THAN 2, USE FORMS G AND H INSTEAD OF C AND D.
6/ SOIL LOSS, SEDIMENT YIELD, AND SEDIMENT STORAGE, FOR EACH SUBWATERSHED IN THE GROUP, WILL BE DETERMINED BASED ON RATES COMPUTED FOR THE SUBWATERSHED DESIGNATED ON THE LINE ABOVE. SEE FORM F.
7/ FOR SUBWATERSHEDS IN SERIES, UPSTREAM SUBWATERSHEDS MUST BE PROCESSED FIRST, AS IN THE EXAMPLE AT RIGHT.



SUBWATERSHED 3: NONE IN SERIES ABOVE (MUST BE PROCESSED BEFORE NO. 4)
SUBWATERSHED 2: NONE IN SERIES ABOVE (MUST BE PROCESSED BEFORE NO. 1)
SUBWATERSHED 4: NO. 3 IS IN SERIES ABOVE (MUST BE PROCESSED BEFORE NO. 5)
SUBWATERSHED 5: NO. 4 IS IN SERIES ABOVE (MUST BE PROCESSED BEFORE NO. 1)
SUBWATERSHED 1: NO. 2 AND NO. 5 ARE IN SERIES ABOVE (MUST BE PROCESSED LAST)

8/ IF ANY BEDLOAD ENTERS THIS SUBWATERSHED FROM UPSTREAM SUBWATERSHEDS, A BEDLOAD DELIVERY RATIO MUST BE ENTERED ON FORM D, LINE 8.

SCS-ENG-309C
JANUARY 1975

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

GROSS EROSION AND SEDIMENT YIELD

SUBWATERSHED – SHEET EROSION DATA

1 11 26 31 36 41 46 51 61 76 80

LAND USE CONTROL WORD	SOIL NAME (IF APPLICABLE)	UNIVERSAL SOIL LOSS EQUATION K	C	SLOPE (%)	SLOPE LENGTH (FT.)	PRACTICE FACTOR 1/	ACRES PRESENT	FUTURE		CARD NO.
CULTIVATED	NATELY	.185	1.	9.	72.6	—	54.	0.		5
CULTIVATED	DANEEKA	.25	.516	9.	72.6	—	0.	50.		6
IDLE	ORR	.2	1.	9.	72.6	.405	15.	0.		7
PASTURE	DREEDLE	.41	1.	9.	72.6	.1	88.	0.		8
PASTURE	DUCKETT	.2	.145	9.	72.6	—	0.	95.		9
WOODLAND	AARDVARK	.2	1.	9.	72.6	.115	63.	0.		10
WOODLAND	CATHCART	.3	.5	9.	72.6	.1	0.	75		11
ENDLIST										12

Allowable Land use control words: (Do Not Abbreviate)

CULTIVATED
IDLE
PASTURE
RANGE
WOODLAND
ENDLIST

Each land use control word may be used as often as needed except "Endlist" which must be used only once (following the final data line).

1/ "P" Factors of 1. need not be entered.

SCS-ENG-309D
JANUARY 1975

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

GROSS EROSION AND SEDIMENT YIELD

SUBWATERSHED — — EROSION DATA (EXCEPT SHEET EROSION)

SHEET 4 OF 5

1 11 21 36 46 51 61 76 80

TYPE OF EROSION AND UNITS	AVERAGE ANNUAL RATE	DELIVERY RATIO %	ACRES, BANK MILES, OR TONS (USE ACTUAL UNITS, NOT A SAMPLE) PRESENT	FUTURE		CARD NO.
~~GULLY EROSION (T/ACRE)~~						
~~FLOOD PLAIN SCOUR (T/ACRE)~~						
~~URBANIZED (T/ACRE)~~						
~~URBANIZING (T/ACRE)~~						
~~MINE SPOIL (T/ACRE)~~						
ROADBANK (T/BANK MILE)	50.	50.	40.	16.		13
STREAMBANK (T/BANK MILE)	20.	90.	60.	60.		14
~~BEDLOAD (TONS)~~			~~1.~~	~~1.~~		
OTHER (SPECIFY)						
GULLYS (TONS)	1.	80.	6600.*	3160.*		15
~~NON-SEDIMENT (CONTRIBUTING AREAS)~~	~~0.~~	~~0.~~				
END LIST						16

Rule out lines for all erosion categories not used.

CARDPUNCH OPERATOR: DO NOT PUNCH CHARACTERS IN PARENTHESES

SCS-ENG-309E
JANUARY 1975

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

GROSS EROSION AND SEDIMENT YIELD
SEDIMENT STORAGE 1/

SHEET 5 OF 5

1	11	21	31	41	51	61	66	76	80

SEDIMENT STORAGE OPTIONS 2/ FOR A PROPOSED DAM SITE						% OF AERATED SED. BTW. HI-LO STAGES PS	% OF SUBM. SED. IN BENEF. POOL		CARD NO.
SINGLE PURPOSE				MULTI-PURPOSE					
NORMAL POOL		DRY DAM							
TRAP EFFICIENCY	% SED. SUBMERGED	TRAP EFFICIENCY	% SED. SUBMERGED	TRAP EFFICIENCY	% SED. SUBMERGED				
95.	80.	—	—	—	—	70.	—		17

VOLUME - WEIGHT OF - SEDIMENT (LBS./CU. FT.)		TEXTURE OF INCOMING SEDIMENT					CARD NO.
SUBMERGED	AERATED	% CLAY	% SILT	% SAND	% GRAVEL		
50.	82.	30.	40.	20.	10.		18

1/ FOR THE SITE ON THE PRECEEDING FORMS B, C, AND D.

2/ IF SEDIMENT ROUTING FOR THE WATERSHED IS SPECIFIED ON FORM A, SELECT ONLY ONE OF THESE THREE OPTIONS. IF SEDIMENT ROUTING IS NOT SPECIFIED ON FORM A, YOU MAY SPECIFY ANY ONE, ANY TWO, OR ALL THREE SEDIMENT STORAGE OPTIONS.

```
SEDIMENT STORAGE PROCEDURE - EXAMPLE                            100. 01
A. COMPETENT          GEOLOGIST       07/04/82
WETT CREEK W/S SITE NO. 7       2200.        2200.       220.   20.  100.  100.  010
 2    8.    92.
CULTIVATED  NATELY          .185 1.    9.    72.6        54.         0.
CULTIVATED  DANEEKA         .25  .516  9.    72.6        0.          50.
IDLE        ORR             .2   1.    9.    72.6  .405  15.         0.
PASTURE     DREEDLE         .41  1.    9.    72.6  .1    88.         0.
PASTURE     DUCKETT         .2   .145  9.    72.6        0.          95.
WOODLAND    AARDVARK        .2   1.    9.    72.6  .115  63.         0.
WOODLAND    CATHCART        .3   .5    9.    72.6  .1    0.          75.
ENDLIST
ROADBANK                           50.         50.   40.         16.
STREAMBANK                         20.         90.   60.         60.
        GULLYS                     1.          80.   6600.       3160.
ENDLIST
95.         80.                                                  70.
50.         82.         30.         40.         20.         10.
```

EXECUTE DATE 07/26/82

SEDIMENT STORAGE PROCEDURE - EXAMPLE BY A. COMPETENT GEOLOGIST 07/04/82

GROSS EROSION AND SEDIMENT YIELD FOR

WETT CREEK W/S SITE NO. 7 2200. ACRES (3.44 SQUARE MILES)

SEDIMENT YIELD BY SOURCES (AVERAGE ANNUAL)

	FIRST 8.0 YEARS					YEARS 8.1 THROUGH 100.0				
	ACRES	SOIL LOSS (T/AC)	TOTAL SOIL LOSS (TONS)	DEL. RATIO (PCT)	SEDIMENT YIELD (TONS)	ACRES	SOIL LOSS (T/AC)	TOTAL SOIL LOSS (TONS)	DEL. RATIO (PCT)	SEDIMENT YIELD (TONS)
CULTIVATED	540.	18.50	9990.	20.	1998.	500.	12.90	6450.	20.	1290.
IDLE	150.	8.10	1215.	20.	243.	0.	0.0	0.	20.	0.
PASTURE	880.	4.10	3608.	20.	722.	950.	2.90	2755.	20.	551.
WOODLAND	630.	2.30	1449.	20.	290.	750.	1.50	1125.	20.	225.
ROADBANK	40.	50.00	2000.	50.	1000.	16.	50.00	800.	50.	400.
STREAMBANK	60.	20.00	1200.	90.	1080.	60.	20.00	1200.	90.	1080.
GULLYS		1.00	6600.	80.	5280.		1.00	3160.	80.	2528.
NON-SEDIMENT CONTRIBUTING	0.					0.				
TOTAL ACRES	2200.					2200.				
ANNUAL TOTALS			26062.		10612.			15490.		6074.
PERIOD TOTALS			208496.		84899.			1425077.		558807.

ROADBANK UNITS (IN ACRES COLUMN) ARE BANK MILES
STREAMBANK UNITS (IN ACRES COLUMN) ARE BANK MILES
GULLYS HAS NO AREA OR LENGTH UNITS

GROSS EROSION IS 1633572. TONS (4752. TONS/SQ MI/YR)
SEDIMENT YIELD IS 643706. TONS (1873. TONS/SQ MI/YR)
DELIVERY RATIO IS 39. PER CENT

EXECUTE DATE 07/26/82

SEDIMENT STORAGE PROCEDURE - EXAMPLE BY A. COMPETENT GEOLOGIST 07/04/82

SEDIMENT STORAGE FOR

WETT CREEK W/S SITE NO. 7 2200. ACRES (3.44 SQUARE MILES)

FOR A SINGLE-PURPOSE FLOODWATER DAM WITH NORMAL POOL FOR 100.0 YEARS

TRAP EFFICIENCY IS 95. PERCENT
SEDIMENT IS 80. PERCENT SUBMERGED AND 20. PERCENT AERATED

	TONS	ACRE FEET	W/S INCHES
SUBMERGED SEDIMENT	489217.	449.2	2.45
AERATED SEDIMENT	122304.	68.5	0.37
TOTAL STORED	611521.	517.7	2.82

47.9 ACRE FEET (70. PER CENT) OF THE AERATED SEDIMENT IS BETWEEN P.S. HIGH AND LOW STAGES

TEXTURE OF INCOMING SEDIMENT
30. PERCENT CLAY
40. PERCENT SILT
20. PERCENT SAND
10. PERCENT GRAVEL

DENSITY OF SUBMERGED SEDIMENT IS 50. PCF

DENSITY OF AERATED SEDIMENT IS 82. PCF

SEDIMENT PASSING THE SITE IS 32185. TONS

United States
Department of
Agriculture

Soil
Conservation
Service

National Engineering Handbook

Section 3

Sedimentation

Chapter 9

Units and Equivalents

Contents

Page
General 9-1
Metric system (SI) conversion 9-1
Rules for style and usage 9-2
Conversion factors 9-2
Other conversions 9-8
References 9-15

Figures

Page

9–1. Conversion of tons to acre-feet for various volume-weights 9-9

Tables

Page

9–1. Base units of the International System (SI) 9-1
9–2. Prefixes for use in multiples of International System (SI) units 9-2
9–3. Conversion factors for hydraulic volumes 9-11
9–4. Greek alphabet 9-11
9–5. Map scales and area equivalents 9-12
9–6. Volume-weight conversions 9-13
9–7. Conversion of inches to feet 9-14

Chapter 9
Units and Equivalents

General

Various lists, tables, and charts are included in this section for the convenience of geologists compiling information on rates, volumes, and quantities of sediment, rock formations, and geologic processes. The only explanations in the tables and charts are those necessary to give the basis for the information presented. The conversion factors shown are generally four significant digits; more precise conversion factors of five or more significant digits may be needed in some instances. In all conversions, retain enough significant digits to ensure that accuracy is neither sacrificed nor exaggerated.

Metric System (SI) Conversion

Most of the procedures, formulas, and tables in this handbook are presented in English units. Conversion factors are included in this chapter for those who wish to use the metric system. Table 9–1 shows pertinent base units of the International System of Units (SI), and table 9–2 shows prefixes to be used with SI units.

Table 9–1.—Base units of the International System (SI)

	Base unit	
Quantity	Name	Symbol
Length	meter (metre)[1]	m
Mass[2]	kilogram	kg
Time	second	s

[1]Both spelling are acceptable.
[2]Weight is the commonly used term for mass.

Table 9-2.—Prefixes for use in multiples of International System (SI) units

Mutiplier	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto[a]	h
10^{1}	deka[a]	da
10^{-1}	deci[a]	d
10^{-2}	centi[a]	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

[a]These prefixes are generally not recommended. Multiples of 1,000 are preferred.

Rules for Style and Usage

The choice of the appropriate prefix (multiplier) of an SI unit is governed by convenience. The multiple chosen for a particular application is the one that yields numerical values within a practical range.

Use a slash (/) to form a compound unit by dividing one unit by another, e.g., m/s, kg/m².

Area or volume units are indicated by the appropriate superscript, e.g., km² or m³.

Do not use multiple prefixes, such as dkm or μml.

Conversion Factors

To Convert	Into	Multiply By
A		
acre	hectares or square hectometers	0.4047
	square feet (sq ft)[a]	43,560.
	square meters (m²)	4,047.
	square miles (sq mi)	1.562×10^{-3}
acre-feet (acre-ft)	cubic feet (cu ft)	43,560
	cubic yards (cu yd)	1,613.
	gallons (gal)	325,850.
	megaliters (ML)	1.234
	cubic meters (m³)	1,234.
	cubic dekameters (dam³)	1.234
	acre-inches	12.00
acre-feet/square mile (acre-ft/sq mi)	cubic feet/acre	68.06
	tons/square mile (T/sq mi)	See fig. 9–1
	tons/acre	See fig. 9–1[b]
	watershed inches	0.01875
	cubic meters/square kilometer (m³/km²)	476.3
acre-feet of water	tons	1,359.
	cubic dekameters (dam³)	1.234
	megagrams (Mg)	1,234.

[a]These abbreviations may be used when their meaning is clear; otherwise spell them out.

[b]After getting tons/square mile from figure 9–1, multiply by 1.56×10^{-3} to convert to tons/acre.

To Convert	Into	Multiply By
acre-inches	acre-feet (acre-ft)	0.08333
	cubic feet (cu ft)	3,630.
C		
Celsius (C)	Fahrenheit (F)	1.8C + 32
centimeters (cm)	feet (ft)	0.03281
	inches (in)	0.3937
	meters (m)	0.010
	millimeters (mm)	10.00
centimeters/second (cm/s)	feet/minute (ft/min)	1.197
cubic centimeters (cm^3)	cubic feet (cu ft)	3.531×10^{-5}
	cubic inches (cu in)	0.06102
	U.S. gallons (U.S. gal)	2.642×10^{-4}
	liters (L)	0.001
	U.S. pints	2.113×10^{-3}
	U.S. quarts	1.057×10^{-3}
cubic dekameters (dam^3)	acre-feet (acre-ft)	0.8104
cubic feet (cu ft)	cubic centimeters (cm^3)	28,320.
	cubic inches (cu in)	1,728.
	cubic meters (m^3)	0.02832
	cubic yards (cu yd)	0.03704
	U.S. gallons (U.S. gal)	7.481
	liters (L)	28.32
cubic feet/acre	acre-inches	2.754×10^{-4}
	acre-feet (acre-ft)	2.296×10^{-5}
cubic feet of water	pounds (lb)	62.43
	kilograms/square centimeter (kg/cm^2)	0.03048
	kilograms/square meter (kg/m^2)	304.8
	pounds/square foot (psf)	62.43
	pounds/square inch (psi)	0.4335
cubic feet/second (cfs)	acre-feet per day (acre-ft/d)	1.984
	acre-feet per year (acre-ft/yr)	724.0
	gallons/minute (gpm)	448.8
	million gallons/day (mgd)	0.6463
	cubic meters/second (m^3/s)	0.02832
	liters/second (L/s)	28.32
cubic feet/second/square mile (csm)	liters/second/square kilometer ($L/s/km^2$)	0.0915
cubic feet/second-days	cubic feet	86,400.
cubic inches (cu in)	cubic centimeters (cm^3)	16.39
	cubic feet (cu ft)	5.787×10^{-4}
cubic meters (m^3)	cubic feet (cu ft)	35.32
	U.S. gallons (U.S. gal)	264.2
	cubic yards (cu yd)	1.308
cubic meters/second (m^3/s)	million gallons/day (M gal/d)	22.83
cubic meters/square kilometer (m^3/km^2)	acre-feet/square mile	21.0×10^{-4}
cubic mile (U.S. statute)	acre-feet (acre-ft)	3.379×10^{6}
cubic yards (cu yd)	cubic centimeters (cm^3)	7.646×10^{5}

To Convert	Into	Multiply By
	cubic feet (cu ft)	27.0
	cubic meters (m^3)	0.7646
	acre-feet (acre-ft)	6.19×10^{-4}
D		
days	seconds (s)	86,400.
degrees Fahrenheit (F)	degrees Celsius (C)	(F°–32)0.5556
F		
Fahrenheit (F)	Celsius (C)	(F°–32)0.5556
feet (ft)	centimeters (cm)	30.48
	kilometers (km)	3.048×10^{-4}
feet (ft)	meters (m)	0.3048
	miles (mi)	1.894×10^{-4}
feet/minute (fpm)	centimeters/second (cm/s)	0.5080
	feet/second (fps)	0.01667
	kilometers/hour (km/h)	0.01829
	miles/hour (mi/h)	0.01136
feet/second (fps)	meters/minute (m/min)	18.29
	meters/second (m/s)	0.3048
	miles/hour (mph)	0.6818
	kilometers/hour (km/h)	1.097
G		
gallons (U.S.)	cubic centimeters (cm^3)	3,785.0
	cubic feet (cu ft)	0.1337
	cubic inches (cu in)	231.0
	cubic meters (m^3)	0.003785
	gallons-British Imperial (gal Br. Imp.)	0.8327
	liters (L)	3.785
gallons of water	pounds of water	8.3453
gallons/minute (gpm)	cubic feet/second (cfs)	2.228×10^{-3}
	cubic meters/day (m^3/d)	5.451
	liters/second (L/s)	0.06308
	cubic feet/hour (cu ft/h)	8.0208
grams	pounds (lb)	2.205×10^{-3}
grams of water	cubic centimeters of water (cm^3 of H_2O)	1.0 (at 4°C)
grams/cubic centimeter (g/cm^3)	kilograms/cubic meter (kg/m^3)	1,000.
grams/cubic meter (g/m^3)	parts/million (ppm)	1.0[c]
H		
hectares	acres	2.471
	square feet (sq ft)	1.076×10^{-5}
hours (h)	days (d)	0.04167
	weeks (wk)	5.952×10^{-3}

[c] *True within 1 percent when concentration is less than 1,000 ppm (g/m^3 = mg/L).*

To Convert	Into	Multiply By
I		
inches (in)	centimeters (cm)	2.540
inches (watershed)	cubic feet/second/square mile (csm)	13.584
inches eroded	tons (t)[d]	1.815 × volume wt (pcf) of upland soil
K		
kilograms (kg)	pounds, avoirdupois (lb)	2.205
	tons (T)	1.102×10^{-3}
	megagrams (Mg) or tonnes	1×10^{-3}
kilograms/second (kg/sec)	tons/year (T/yr)	34,786.
kilograms/cubic meter (kg/m^3)	pounds/cubic foot (pcf)	0.06243
kilometers (km)	miles (mi)	0.6214
L		
liters (L)	cubic centimeters (cm^3)	1,000.
	cubic feet (cu ft)	0.03531
	gallons (gal)	0.2642
liters/second	cubic feet/second (cfs)	0.03531
liters/second/square kilometer ($L/s/km^2$)	cubic feet/second/square mile (csm)	10.93
M		
megagrams (Mg)	tons (T)	1.1023
megagrams/square kilometer (Mg/km^2)	tons/square mile	2.8571
megaliters (ML)	acre-feet (acre-ft)	0.8104
meters (m)	yards (yd)	1.094
	feet (ft)	3.281
	inches (in)	39.37
	miles, U.S. Stat. (mi)	6.214×10^{-4}
meters/second (m/s)	feet/second (ft/sec)	3.281
micrometer (μm)	meters (m)	1.0×10^{-6}
	cubic dekameters (dam^3)	1.0
miles, U.S. Stat. (mi)	kilometers (km)	1.609
miles/hour (mph)	feet/second (fps)	1.467
milliliters (ml)	liters (L)	1.0×10^{-3}
millimeters (mm)	inches (in)	0.03937
	micrometers (μm)	1.0×10^{-3}
million gallons/day (mgd)	cubic feet/second (cfs)	1.547
	acre-feet/day	3.069
	cubic/meters/minute (m^3/min)	2.629
minutes, angular (min)	degrees (deg)	0.01667

[d] *Tons means short tons (2,000 lb) unless otherwise indicated.*

To Convert	Into	Multiply By
O		
ounces (oz)	grams (g)	28.35
	pounds (lb)	0.0625
ounces/gallon (U.S.) (oz/gal-U.S.)	grams/liter (gm/L)	7.489
P		
parts per million (ppm)	grams/cubic meter (g/m³)	1.0[e]
pounds (lb)	grains	7,000.
	grams (g)	453.6
	kilograms (kg)	0.4536
	ounces (oz)	16.00
	tons	0.0005
pounds of water	cubic feet (cu ft)	0.01602
	cubic inches (cu in)	27.68
	gallons (gal)	0.1198
pounds of water/minute	cubic feet/second (cfs)	2.670×10^{-3}
pounds/cubic foot (pcf)	grams/cubic centimeter (g/cm³)	0.01602
	kilograms/cubic meter (kg/m³)	16.02
pounds/cubic inch	grams/cubic centimeter (g/cm³)	27.68
pounds/gallon (U.S.)	grams/liter (g/L)	119.8
pounds/cubic foot (pcf)	tons/acre-foot (T/acre-ft)	21.78
	kilograms/cubic meter (kg/m³)	16.02
pounds/square foot (psf)	pounds/square inch (psi)	6.944×10^{-3}
pounds/second/foot	kilograms/second/meter	1.488
R		
rods	feet (ft)	16.50
	miles (mi)	3.125×10^{-3}
S		
seconds (s)	days	1.157×10^{-5}
square centimeters (cm²)	square inches (sq in)	0.1550
square feet (sq ft)	acres	2.296×10^{-5}
	square meters (m²)	0.0929
square inches (sq in)	square centimeters (cm²)	6.452
square kilometers (km²)	square miles (sq mi)	0.3861
	acres	247.1
square meters (m²)	square feet (sq ft)	10.76
	square yards (sq yd)	1.196
square miles (sq mi)	acres	640.0
	square feet (sq ft)	27.88×10^{6}
	square kilometers (km²)	2.590
	square meters (m²)	2.590×10^{6}
	square yards (sq yd)	3.098×10^{6}
square yards (sq yd)	square feet (sq ft)	9.000
	square meters (m²)	0.8361

[e] *True within 1 percent when concentration is less than 10,000 ppm (g/m³ = mg/L).*

To Convert	Into	Multiply By
T		
tonnes	tons	1.103
	pounds (lb)	2,205.
	megagrams (Mg)	1.000
tons (long)	pounds (lb)	2,240.
	tons	1.102
	pounds (lb)	2,205.
tons	kilograms (kg)	907.2
	megagrams (Mg)	0.9072
	pounds (lb)	2,000.
	tons (long)	0.8929
	tonnes	0.9072
tons/square mile	acre-feet/square mile (acre-ft/sq mi)	See fig. 9–1A and B
	megagrams/square kilometer (Mg/km^2)	0.350
	tons/acre (T/acre)	1.5625×10^{-3}
tons of water/24 hr	pounds of water/hour	83.33
	gallons/minute (gpm)	0.1664
	cubic feet/hour (cu ft/hr)	1.335
tons/acre-foot	pounds/cubic foot (pcf)	0.04591
W		
watershed inches	acre-feet/square mile (acre-ft/sq mi)	53.33
	acre-feet (total)	53.33 × drainage area in sq mi

Figures 9–1A and 9–1B are charts for converting various volume-weights or weights of sediment per acre-foot to tons. Table 9–3 is convenient for conversions of hydraulic or sedimentation data. Table 9–4 shows the Greek alphabet. Table 9–5 shows map scales and equivalents for use with aerial photographs and U.S. Geological Survey quadrangles. Table 9–6 illustrates conversion of volume-weight between pounds per cubic foot and tons per acre-foot. Table 9–7 shows conversion of inches to feet.

Suspended sediment and sediment yield can be converted from parts per million by weight to tons as follows:

$$\frac{\text{ppm} \times \text{discharge (cu ft per period)} \times 62.4}{1{,}000{,}000 \times 2{,}000 \text{ (or } 2 \times 10^9)}$$

$$= \text{sediment yield (tons per period)}$$

$$\frac{\text{ppm} \times \text{cfs} \times 86{,}400 \times 62.4}{2 \times 10^9} = \text{ppm} \times \text{cfs}$$

$$\times\ 0.0027 = \text{sediment yield (tons per day)}$$

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

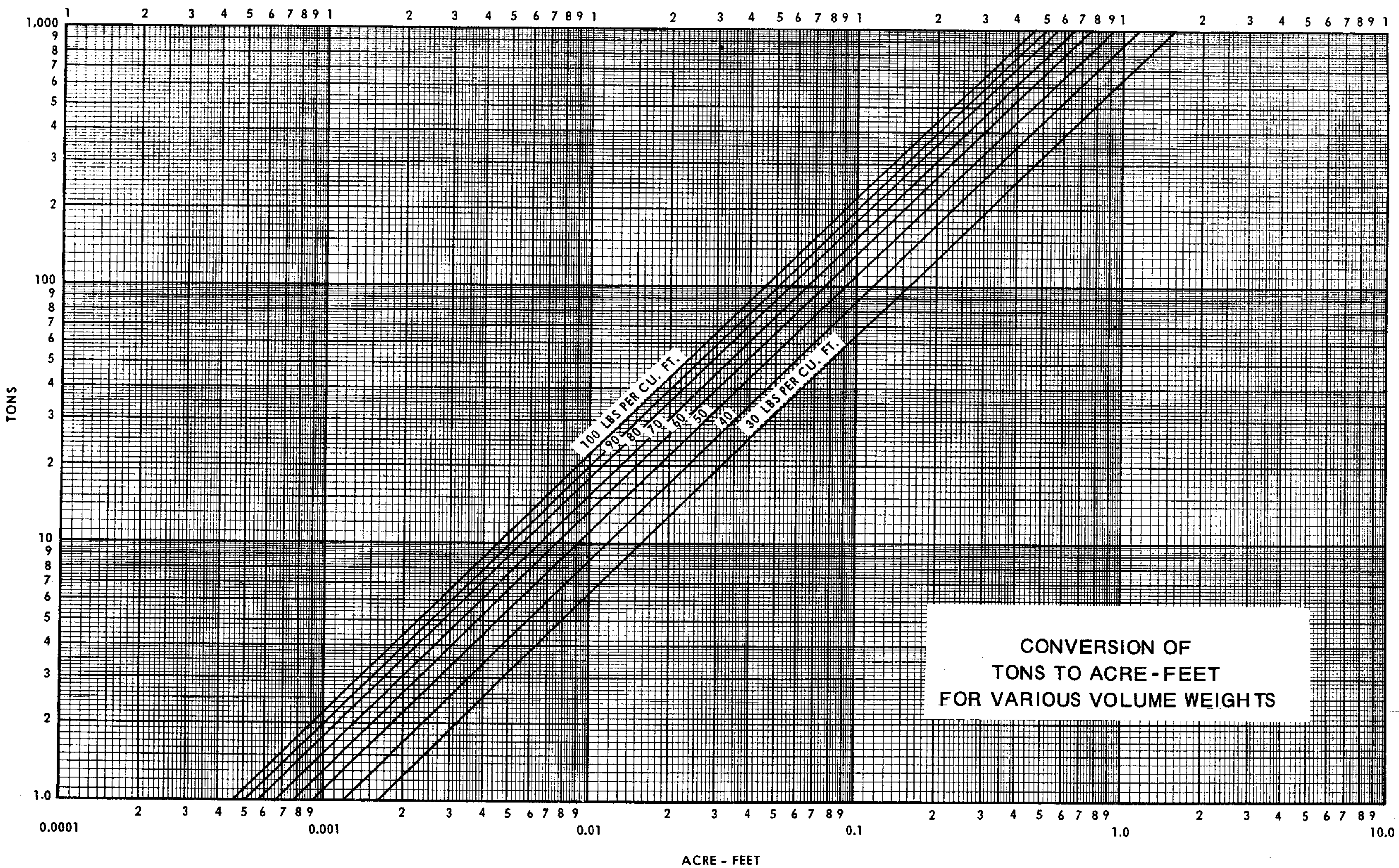


Figure 9–1A.—Conversion of tons to acre-feet for various volume-weights.

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

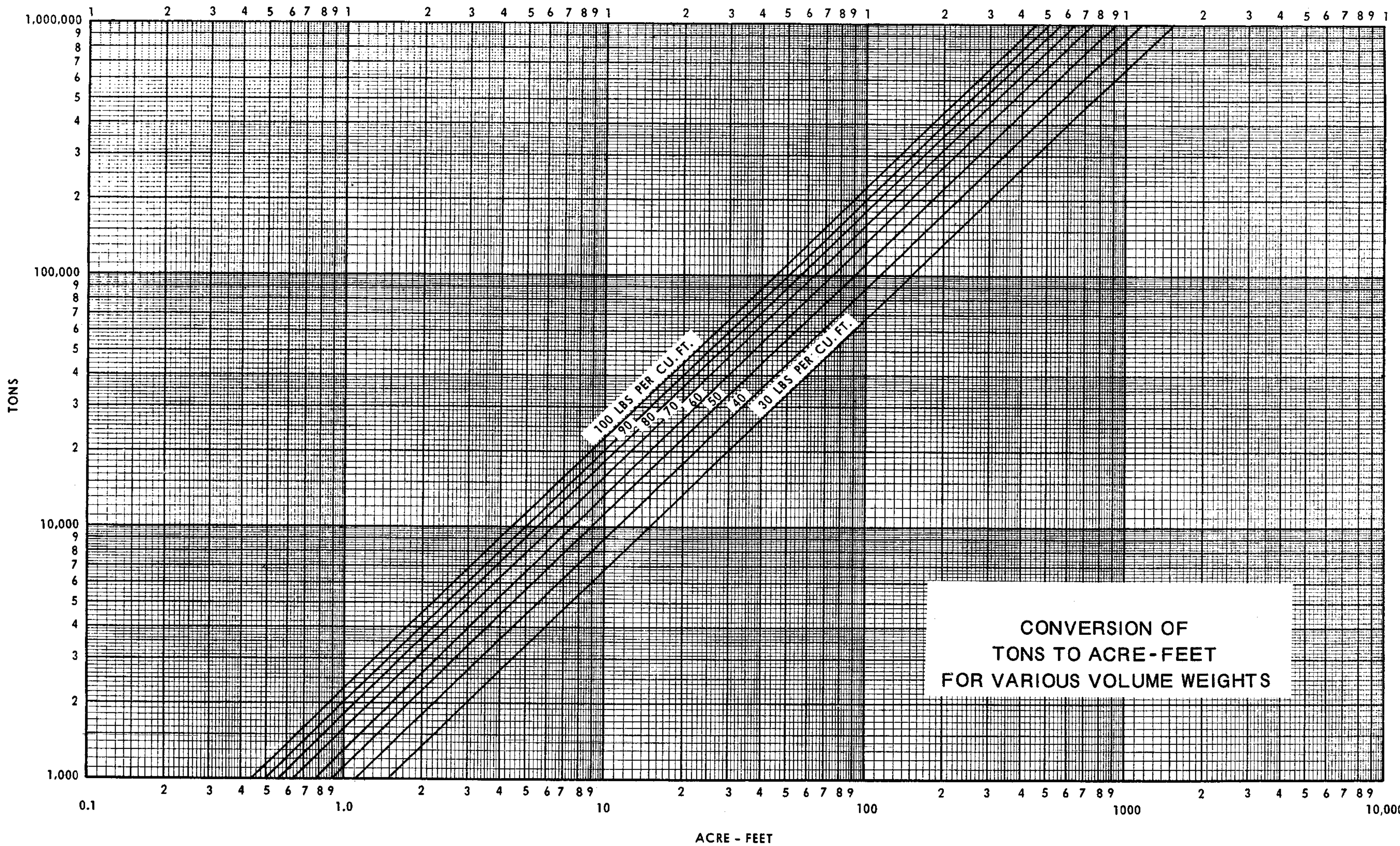


Figure 9–1B.—Conversion of tons to acre-feet for various volume-weights.

Table 9–3.—Conversion factors for hydraulic volumes

Initial unit	Multiplier to obtain:				
	Cfs-days	Cu ft × 10^6	Gal × 10^6	Acre-ft	In/sq mi
Cfs-days	—	0.08640	0.64632	1.9835	0.037190
Cu ft × 10^6	11.574	—	7.4805	22.957	.43044
Gal × 10^6	1.5472	0.13368	—	3.0689	.05742
Acre-ft	0.50417	0.04356	0.32585	—	.018750
In/sq mi	26.889	2.3232	17.379	53.33	—

Table 9–4.—Greek alphabet

Α α alpha	Η η eta	Ν ν nu	Τ τ tau
Β β beta	Θ θ theta	Ξ ξ xi	Υ υ upsilon
Γ γ gamma	Ι ι iota	Ο ο omicron	Φ ϕ phi
Δ δ delta	Κ κ kappa	Π π pi	Χ χ chi
Ε ε epsilon	Λ λ lambda	Ρ ϱ rho	Ψ ψ psi
Ζ ζ zeta	Μ μ mu	Σ ς sigma	Ω ω omega

Table 9–5.—Map scales and area equivalents

Fractional scale	Ft per in.	In. per 1,000 ft	In. per mi	Mi per in.	Meters per in.	Acres per sq. in.	Sq. in. per acre	Sq. mi per sq. in.
1: 500	41.667	24.00	126.72	0.008	12.700	0.0399	25.091	0.00006
1: 600	50.00	20.00	105.60	0.009	15.240	0.0574	17.424	0.00009
1: 1,000	83.333	12.00	63.36	0.016	25.400	0.1594	6.273	0.00025
1: 1,200	100.00	10.00	52.80	0.019	30.480	0.2296	4.356	0.00036
1: 1,500	125.00	8.00	42.24	0.024	38.100	0.3587	2.788	0.00056
1: 2,000	166.667	6.00	31.68	0.032	50.800	0.6377	1.568	0.00100
1: 2,400	200.00	5.00	26.40	0.038	60.960	0.9183	1.089	0.0014
1: 2,500	208.333	4.80	25.344	0.039	63.500	0.9964	1.004	0.0016
1: 3,000	250.00	4.00	21.12	0.047	76.200	1.4348	0.697	0.0022
1: 3,600	300.00	3.333	17.60	0.057	91.440	2.0661	0.484	0.0032
1: 4,000	333.333	3.000	15.84	0.063	101.600	2.5508	0.392	0.0040
1: 4,800	400.00	2.500	13.20	0.076	121.920	3.6731	0.272	0.0057
1: 5,000	416.667	2.400	12.672	0.079	127.000	3.9856	0.251	0.0062
1: 6,000	500.00	2.000	10.56	0.095	152.400	5.7392	0.174	0.0090
1: 7,000	583.333	1.714	9.051	0.110	177.800	7.8117	0.128	0.0122
1: 7,200	600.00	1.667	8.800	0.114	182.880	8.2645	0.121	0.0129
1: 7,920	660.00	1.515	8.000	0.125	201.168	10.00	0.100	0.0156
1: 8,000	666.667	1.500	7.920	0.126	203.200	10.203	0.098	0.0159
1: 8,400	700.00	1.429	7.543	0.133	213.360	11.249	0.089	0.0176
1: 9,000	750.00	1.333	7.041	0.142	228.600	12.913	0.077	0.0202
1: 9,600	800.00	1.250	6.600	0.152	243.840	14.692	0.068	0.0230
1: 10,000	833.333	1.200	6.336	0.158	254.000	15.942	0.063	0.0249
1: 10,800	900.00	1.111	5.867	0.170	274.321	18.595	0.054	0.0291
1: 12,000	1,000.00	1.000	5.280	0.189	304.801	22.957	0.044	0.0359
1: 13,200	1,100.00	0.909	4.800	0.208	335.281	27.778	0.036	0.0434
1: 14,400	1,200.00	0.833	4.400	0.227	365.761	33.058	0.030	0.0517
1: 15,000	1,250.00	0.800	4.224	0.237	381.001	35.870	0.028	0.0560
1: 15,600	1,300.00	0.769	4.062	0.246	396.241	38.797	0.026	0.0606
1: 15,840	1,320.00	0.758	4.000	0.250	402.337	40.000	0.025	0.0625
1: 16,000	1,333.333	0.750	3.960	0.253	406.400	40.812	0.024	0.0638
1: 16,800	1,400.00	0.714	3.771	0.265	426.721	44.995	0.022	0.0703
1: 18,000	1,500.00	0.667	3.520	0.284	457.201	51.653	0.019	0.0807
1: 19,200	1,600.00	0.625	3.300	0.303	487.681	58.770	0.017	0.0918
1: 20,000	1,666.667	0.600	3.168	0.316	508.002	63.769	0.016	0.0996
1: 20,400	1,700.00	0.588	3.106	0.322	518.161	66.345	0.015	0.1037
1: 21,120	1,760.00	0.568	3.000	0.333	536.449	71.111	0.014	0.1111
1: 21,600	1,800.00	0.556	2.933	0.341	548.641	74.380	0.013	0.1162
1: 22,800	1,900.00	0.526	2.779	0.360	579.121	82.874	0.012	0.1295
1: 24,000	2,000.00	0.500	2.640	0.379	609.601	91.827	0.011	0.1435
1: 25,000	2,083.333	0.480	2.534	0.395	635.001	99.639	0.010	0.1557
1: 31,680	2,640.00	0.379	2.000	0.500	804.674	160.000	0.006	0.2500
1: 48,000	4,000.00	0.250	1.320	0.758	1,219.202	367.309	0.003	0.5739
1: 62,500	5,208.333	0.192	1.014	0.986	1,587.503	622.744	0.0016	0.9730
1: 63,360	5,280.00	0.189	1.000	1.000	1,609.347	640.00	0.0016	1.0000
1: 96,000	8,000.00	0.125	0.660	1.515	2,438.405	1,469.24	0.0007	2.2957
1: 125,000	10,416.667	0.096	0.507	1.973	3,175.006	2,490.98	0.0004	3.8922
1: 126,720	10,560.00	0.095	0.500	2.00	3,218.694	2,560.00	0.0004	4.000
1: 250,000	20,833.333	0.048	0.253	3.946	6,350.012	9,963.907	0.0001	15.5686
1: 253,440	21,120.00	0.047	0.250	4.00	6,437.389	10,244.202	0.0001	16.00
1: 500,000	41,666.667	0.024	0.127	7.891	12,700.025	39,855.627	2.5×10^{-5}	62.2744
1:1,000,000	83,333.333	0.012	0.063	15.783	25,400.050	159,422.507	6.2×10^{-6}	249.0977
FORMULAS	$\frac{\text{SCALE}}{12}$	$\frac{12{,}000}{\text{SCALE}}$	$\frac{63{,}360}{\text{SCALE}}$	$\frac{\text{SCALE}}{63{,}360}$	Ft per in. $\times$ 0.3048006	$\frac{(\text{SCALE})^2}{43{,}560 \times 144}$	$\frac{43{,}560 \times 144}{(\text{SCALE})^2}$	$\frac{(\text{Ft per in.})^2}{(5{,}280)^2}$

Table 9-6.—Volume-weight conversions

Lb per cu ft	Tons per acre-ft	Acre-ft per ton	Acre-in. per ton	Tons per acre-in.
30	653.40	0.00153	0.01837	54.45
31	675.18	.00148	.01777	56.27
32	696.96	.00144	.01722	58.08
33	718.74	.00139	.01670	59.90
34	740.52	.00135	.01620	61.71
35	762.30	.00131	.01574	63.53
36	784.08	.00128	.01530	65.34
37	805.86	.00124	.01489	67.16
38	827.64	.00121	.01450	68.97
39	849.42	.00118	.01412	70.79
40	871.20	.00115	.01378	72.60
41	892.98	.00112	.01344	74.42
42	914.76	.00109	.01312	76.23
43	936.54	.00107	.01282	78.05
44	958.32	.00104	.01252	79.86
45	980.10	.00102	.01224	81.68
46	1,001.88	.00100	.01198	83.49
47	1,023.66	.00098	.01172	85.31
48	1,045.44	.00096	.01147	87.12
49	1,067.22	.00094	.01124	88.94
50	1,089.00	.00092	.01102	90.75
51	1,110.78	.00090	.01080	92.57
52	1,132.56	.00088	.01060	94.38
53	1,154.34	.00087	.01039	96.20
54	1,176.12	.00085	.01020	98.01
55	1,197.90	.00084	.01002	99.83
56	1,219.46	.00082	.00984	101.62
57	1,241.46	.00081	.00967	103.46
58	1,263.24	.00079	.00949	105.27
59	1,285.02	.00078	.00934	107.09
60	1,306.80	.00077	.00918	108.90
61	1,328.58	.00075	.00904	110.72
62	1,350.36	.00074	.00889	112.53
62.43	1,359.73	.00074	.00883	113.31
63	1,372.14	.00073	.00875	114.35
64	1,393.92	.00072	.00860	116.16
65	1,415.70	.00071	.00847	117.98
66	1,437.48	.00070	.00834	119.79
67	1,459.26	.00069	.00822	121.61
68	1,481.04	.00068	.00810	123.42
69	1,502.82	.00067	.00798	125.24
70	1,524.60	.00066	.00787	127.05
71	1,546.38	.00065	.00776	128.87
72	1,568.16	.00064	.00764	130.68
73	1,589.94	.00063	.00755	132.50
74	1,611.72	.00062	.00744	134.31
75	1,633.50	.00061	.00734	136.13
76	1,655.28	0.00060	0.00725	137.94
77	1,677.06	.00060	.00715	139.76
78	1,698.84	.00059	.00706	141.57
79	1,720.62	.00058	.00697	143.39
80	1,742.40	.00057	.00689	145.20
81	1,764.18	.00057	.00679	147.02
82	1,785.96	.00056	.00672	148.83
82.65	1,800.12	.00056	.00666	150.01
83	1,807.74	.00055	.00664	150.65
84	1,829.52	.00055	.00655	152.46
85	1,851.30	.00054	.00648	154.28
86	1,873.08	.00053	.00641	156.09
87	1,894.86	.00053	.00634	157.91
88	1,916.64	.00052	.00626	159.72
89	1,938.42	.00052	.00619	161.54
90	1,960.20	.00051	.00612	163.35
91	1,981.98	.00051	.00606	165.17
92	2,003.76	.00050	.00599	166.98
93	2,025.54	.00049	.00592	168.80
94	2,047.32	.00049	.00586	170.61
95	2,069.10	.00048	.00580	172.43
96	2,090.88	.00048	.00574	174.24
97	2,112.66	.00047	.00568	176.06
98	2,134.44	.00047	.00563	177.87
99	2,156.22	.00046	.00557	179.69
100	2,178.00	.00046	.00551	181.50
101	2,199.78	.00046	.00546	183.32
102	2,221.56	.00045	.00540	185.13
103	2,243.34	.00045	.00535	186.95
104	2,265.12	.00044	.00529	188.76
105	2,286.90	.00044	.00524	190.58
106	2,308.68	.00043	.00520	192.39
107	2,330.46	.00043	.00515	194.21
108	2,352.24	.00043	.00510	196.02
109	2,374.02	.00042	.00505	197.84
110	2,395.80	.00042	.00500	199.65
111	2,417.58	.00041	.00497	201.47
112	2,439.36	.00041	.00492	203.28
113	2,461.14	.00041	.00487	205.10
114	2,482.92	.00040	.00484	206.91
115	2,504.70	.00040	.00479	208.73
116	2,526.48	.00040	.00475	210.54
117	2,548.26	.00039	.00470	212.36
118	2,570.04	.00039	.00467	214.17
119	2,591.82	.00039	.00463	215.99
120	2,613.60	.00038	.00460	217.80

Table 9-7.—Conversion of inches to feet

1 in. = 0.08 ft	7 in. = 0.58 ft
2 in. = 0.17 ft	8 in. = 0.67 ft
3 in. = 0.25 ft	9 in. = 0.75 ft
4 in. = 0.33 ft	10 in. = 0.83 ft
5 in. = 0.42 ft	11 in. = 0.92 ft
6 in. = 0.50 ft	12 in. = 1.00 ft

American National Metric Council. 1979. Metric editorial guide. 3d ed. American National Metric Council, 1625 Massachusetts Ave., N.W., Washington, DC 20036, 17 p.

American Society for Testing and Materials. 1980. ASTM standard for metric practice. E 380–79. American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19103, 42 p.

International Organization for Standardization. 1973. SI units and recommendations for the use of their multiples and of certain other units. ISO Standard 1000. American National Standards Institute, 1430 Broadway, New York, NY 10018.

National Bureau of Standards, U.S. Department of Commerce. 1977. The metric system of measurement. NBS Letter Circular 1078.

Zimmerman, O. T., and I. Lavine. 1955. Conversion factors and tables. Industrial Research Service, Inc., Dover, N.H.

☆ U.S. GOVERNMENT PRINTING OFFICE : 1983 O - 418-028